

SURVEY OF CONTEMPORARY
KNOWLEDGE OF
BIOGEOCHEMISTRY

3. THE BIOGEOCHEMISTRY OF
VERTEBRATE EXCRETION

GEORGE EVELYN HUTCHINSON

BULLETIN
OF THE
AMERICAN MUSEUM OF NATURAL HISTORY
VOLUME 96
NEW YORK: 1950

BULLETIN OF
THE AMERICAN MUSEUM
OF NATURAL HISTORY



Volume 96
1950

PUBLISHED BY ORDER OF THE TRUSTEES
NEW YORK : 1950

EDITED BY RUTH TYLER

THE AMERICAN MUSEUM OF NATURAL HISTORY

SEVENTY-NINTH STREET AND CENTRAL PARK WEST, NEW YORK CITY

THE STAFF, 1949-1950

ALBERT E. PARR, Sc.D., Director
WAYNE M. FAUNCE, Sc.B., Vice-Director and Executive Secretary
WALTER F. MEISTER, Assistant Treasurer

SCIENCE AND EDUCATION

ANTHROPOLOGY

H. L. SHAPIRO, Ph.D., Chairman, Curator of
Physical Anthropology
MARGARET MEAD, Ph.D., D.Sc., Associate Cura-
tor of Ethnology
BELLA WEITZNER, Associate Curator of Ethnology
JUNIOUS B. BIRD, Associate Curator of Archae-
ology
GORDON F. EKHOLM, Ph.D., Associate Curator of
Archaeology
JAMES A. FORD, M.A., Assistant Curator of North
American Archaeology
HARRY TSCHOPIK, JR., M.A., Assistant Curator
of Ethnology
CLARENCE L. HAY, A.M., Research Associate
ROBERT VON HEINE-GELDERN, Ph.D., Research
Associate
RALPH LINTON, Ph.D., Research Associate
WILLIAM DUNCAN STRONG, Ph.D., Research
Associate
FREDERICK H. OSBORN, Litt.D., Sc.D., LL.D.,
Honorary Associate
ANTOINETTE K. GORDON, Associate

MAMMALS

HAROLD E. ANTHONY, D.Sc., Chairman and
Curator
CHILDS FRICK, D.Sc., Honorary Curator of Late
Tertiary and Quaternary Mammals
G. H. H. TATE, D.Sc., Curator
GEORGE G. GOODWIN, Associate Curator
T. DONALD CARTER, Assistant Curator
RICHARD ARCHBOLD, Research Associate
ARTHUR S. VERNAY, Field Associate
WILLIAM D. CAMPBELL, Field Associate

BIRDS

ROBERT CUSHMAN MURPHY, Sc.D., Chairman and
Lamont Curator of Birds
JOHN T. ZIMMER, D.Sc., Curator

ERNST MAYR, Ph.D., Curator of the Whitney-
Rothschild Collections
CHARLES E. O'BRIEN, Assistant Curator
E. THOMAS GILLIARD, Assistant Curator
DEAN AMADON, Ph.D., Assistant Curator
ELSIE M. B. NAUMBURG, Research Associate
CHARLES K. NICHOLS, Research Associate and
Honorary Librarian
JEAN DELACOUR, Lic.Sci., Research Associate
CHARLES VAURIE, D.D.S., Research Associate
WILLIAM H. PHELPS, Dr. Hon. Causa, Research
Associate

AMPHIBIANS AND REPTILES

CHARLES M. BOGERT, A.M., Chairman and Cu-
rator
BESSIE MATALAS HECHT, A.B., Scientific As-
sistant
HARVEY BASSLER, Ph.D., Sc.D., Research Asso-
ciate
JOHN A. MOORE, Ph.D., Research Associate
JAMES A. OLIVER, Ph.D., Research Associate
EMMETT R. DUNN, Ph.D., Research Associate
ROGER CONANT, Research Associate
ARCHIE F. CARR, JR., Ph.D., Research Associate
LLEWELLYN THOMAS EVANS, Ph.D., Research
Associate

FISHES AND AQUATIC BIOLOGY

C. M. BREDER, JR., Sc.D., Chairman and Curator
JOHN T. NICHOLS, A.B., Curator of Fishes
FRANCESCA R. LAMONTE, B.A., Associate Cura-
tor of Fishes and Museum Secretary for In-
ternational Game Fish Association Affairs
JOHN C. ARMSTRONG, A.B., Assistant Curator of
Invertebrates
PRISCILLA RASQUIN, A.B., Scientific Assistant
WILLIAM BEEBE, Sc.D., Research Associate in
Fishes
CHRISTOPHER W. COATES, Research Associate in
Fishes

DANIEL MERRIMAN, Ph.D., Research Associate in Oceanography
 FRANK J. MYERS, Research Associate in Rotifers
 HORACE W. STUNKARD, Ph.D., Research Associate in Parasitology
 LIBBIE H. HYMAN, Ph.D., Sc.D., Research Associate in Invertebrates
 H. E. CRAMPTON, Ph.D., Sc.D., Research Associate in Mollusks
 WILLIAM J. CLENCH, M.S., Research Associate in Mollusks
 VAN CAMPEN HEILNER, M.S., Field Representative
 MICHAEL LERNER, Field Associate
 ROSWELL MILLER, JR., C.E., Field Associate
 WYLLYS ROSSETER BETTS, JR., Field Associate

INSECTS AND SPIDERS

MONT A. CAZIER, Ph.D., Chairman and Associate Curator
 C. H. CURRAN, D.Sc., Curator
 WILLIS J. GERTSCH, Ph.D., Associate Curator
 FREDERICK H. RINDGE, Ph.D., Assistant Curator
 HERBERT F. SCHWARZ, M.A., Research Associate
 ERNEST L. BELL, Research Associate
 CYRIL F. DOS PASSOS, LL.B., Research Associate
 ALFRED E. EMERSON, Ph.D., Research Associate
 E. IRVING HUNTINGTON, Research Associate
 ALEXANDER B. KLOTS, Ph.D., Research Associate
 HERMAN T. SPIETH, Ph.D., Research Associate
 WILLIAM P. COMSTOCK, B.A., Research Associate
 JAMES H. MCDUNNOUGH, Ph.D., Research Associate
 CHARLES D. MICHENER, Ph.D., Research Associate

ANIMAL BEHAVIOR

LESTER R. ARONSON, Ph.D., Chairman and Associate Curator
 T. C. SCHNEIRLA, Sc.D., Curator
 A. MARIE TUCKER, M.A., Scientific Assistant
 FRANK A. BEACH, Ph.D., Research Associate
 MYRON GORDON, Ph.D., Research Associate
 CARYL P. HASKINS, Ph.D., Research Associate
 BERNARD F. RIESS, Ph.D., Research Associate
 W. DOUGLAS BURDEN, M.A., Honorary Associate
 BARBARA BOGGS, Honorary Associate

FORESTRY AND GENERAL BOTANY

HENRY K. SVENSON, Ph.D., Chairman and Curator
 CLARENCE L. HAY, A.M., Honorary Curator
 CHARLES RUSSELL, Ph.D., Associate
 RICHARDSON L. WRIGHT, M.A., Research Associate

GEOLOGY AND PALEONTOLOGY

GEORGE GAYLORD SIMPSON, Ph.D., Sc.D., Chairman and Curator of Fossil Mammals and Birds

EDWIN H. COLBERT, Ph.D., Curator of Fossil Reptiles and Amphibians
 NORMAN D. NEWELL, Ph.D., Curator of Historical Geology and Fossil Invertebrates
 FREDERICK H. POUGH, Ph.D., Curator of Physical Geology and Mineralogy
 OTTO H. HAAS, Ph.D., LL.D., Associate Curator of Fossil Invertebrates
 BOBB SCHAEFFER, Ph.D., Associate Curator of Fossil Fishes
 RACHEL HUSBAND NICHOLS, A.M., Scientific Assistant
 HORACE ELMER WOOD, 2ND, Ph.D., Research Associate in Fossil Mammals
 ERICH M. SCHLAIKJER, Ph.D., Research Associate in Fossil Reptiles
 LOUIS HUSSAKOF, Ph.D., Research Associate in Fossil Fishes
 J. BROOKES KNIGHT, Ph.D., Research Associate in Fossil Invertebrates
 ARTHUR K. MILLER, Ph.D., Research Associate in Fossil Invertebrates

MICROPALAEONTOLOGY

BROOKS F. ELLIS, Ph.D., Chairman and Curator
 ANGELINA R. MESSINA, M.A., Associate Curator
 ELEANOR S. SALMON, Ph.D., Scientific Assistant
 HANS E. THALMANN, Ph.D., Research Associate
 MAYNARD P. WHITE, Ph.D., Research Associate
 STANLEY G. WISSLER, M.A., Research Associate

ASTRONOMY AND THE HAYDEN PLANETARIUM

GORDON A. ATWATER, Chairman and Curator
 ROBERT R. COLES, Associate Curator
 CATHARINE E. BARRY, Assistant Curator
 FRED RAISER, Supervising Technician
 SHIRLEY I. GALE, B.S., Special Lecturer
 KENNETH J. HEUER, Special Lecturer
 FRANK H. FORRESTER, Special Lecturer
 EUGENE L. BENEDICT, Special Lecturer
 CLARENCE V. LEE, Special Lecturer
 HENRY M. NEELY, Special Lecturer
 HUGH S. RICE, A.M., Research Associate

EDUCATION

CHARLES RUSSELL, Ph.D., Chairman
 GRACE FISHER RAMSEY, Ph.D., Curator of School Relations
 JOHN R. SAUNDERS, M.A., Associate Curator
 GEORGE F. MASON, Associate Curator
 WILLIAM A. BURNS, Ed.D., Associate Curator
 WINFIELD G. DOYLE, Ed.D., Associate Curator
 JOHN C. ORTH, Assistant Curator

THE STAFF

v

MARGUERITE R. ROSS, M.A., Assistant Curator
FARIDA A. WILEY, Instructor
ALMEDA JOHNSON, Instructor
LUCY W. CLAUSEN, Ph.D., Instructor
INEZ E. BORDNER, B.A., Instructor
HESTER RICH HOPKINS, M.A., Instructor
HAZEL L. MULLER, B.A., Supervisor of Dance
and Lecture Programs
KATHARINE BENEKER, Supervisor of Special Ex-
hibition
ETTA FALKNER, M.A., Associate Supervisor of
Special Exhibition
ANNA MONTGOMERY, Supervisor of Guest Services
MARGUERITE NEWGARDEN, M.A., Supervisor of
Museum Service Center
RICHARD T. MCINTOSH, Supervisor of Sales and
Services

LIBRARY

HAZEL GAY, Librarian
HELEN M. GUNZ, B.A., Assistant Librarian

RICHARD H. POUGH, Curator, Conservation and
Use of Natural Resources
G. EVELYN HUTCHINSON, M.A., Consultant in
Biogeochemistry
J. HOWARD MCGREGOR, Ph.D., Research Associ-
ate, Comparative Anatomy
DUDLEY J. MORTON, M.D., Research Associate,
Comparative Anatomy

EXHIBITION AND PUBLICATION

ARCHITECTURAL DESIGN

JOHN E. PARADIS, Staff Architect
JOSEPH M. GUERRY, Assistant to the Staff Archi-
tect

PREPARATION AND INSTALLATION

GEORGE E. PETERSEN, Chief of Preparation
GEORGE H. CHILDS, Ph.D., Staff Associate
JAMES PERRY WILSON, B.A., B.Ar., Staff Associ-
ate

ILLUSTRATORS CORPS

THOMAS W. VOTER, Supervisor

SCIENTIFIC PUBLICATIONS

RUTH TYLER, M.A., Editor

MAN AND NATURE PUBLICATIONS

WINFIELD G. DOYLE, Ed.D., Editor

NATURAL HISTORY MAGAZINE

EDWARD MOFFAT WEYER, Jr., Ph.D., Editor
ROBERT EDGAR WILLIAMSON, Production Man-
ager
CHARLES J. O'CONNOR, B.S., Manager of Circula-
tion and Advertising

THE JUNIOR NATURAL HISTORY MAGAZINE

DOROTHY LEE EDWARDS, Editor
MARION B. CARR, Associate Editor
CHARLES J. O'CONNOR, B.S., Manager of Circu-
lation and Advertising

PRINT SHOP

EDWARD A. BURNS, Supervisor

BUSINESS ADMINISTRATION

EDWIN C. MEYENBERG, Bursar
ROBERT J. SEIBERT, Chief Accountant
ADRIAN L. WARD, Personnel Officer
WILLIAM F. MUSSIG, Purchasing Agent
CHARLES J. O'CONNOR, B.S., Membership Secre-
tary

DANA P. KELLY, M.A., Resident Director of
Public Relations¹
DORATHEA M. SIEGLE, Executive Assistant, Mu-
seum Contributors Program
ELLA B. RANSOM, Executive Assistant to the
President

¹ Representing Reuel Estill and Company, Inc.

THE STAFF

BUILDING OPERATION AND MAINTENANCE

REX P. JOHNSON, B.A.Sc., General Superintendent
 WILSON L. TODD, Plant Engineer
 LOUIS W. KINZER, Custodian

HENRY H. RAMSHAW, Mechanical Superintendent
 BLANCHE PRESTON, B.A., Manager of Food Services

ADVISORY COMMITTEES

COUNCIL OF THE SCIENTIFIC STAFF

CHARLES M. BOGERT, Dean
 HARRY L. SHAPIRO, Assistant Dean
 LESTER R. ARONSON, Secretary
 The Chairmen of Curatorial Departments

EXHIBITION

Director ALBERT E. PARR, Chairman
 F. TRUBEE DAVISON
 WILLIAM H. LATHAM
 W. DOUGLAS BURDEN
 H. L. SHAPIRO
 WAYNE M. FAUNCE
 HAROLD E. ANTHONY
 CHARLES RUSSELL
 ERNST MAYR
 Dean of the Council

BUDGET

Vice-Director WAYNE M. FAUNCE, Chairman
 F. TRUBEE DAVISON
 WILLIAM H. LATHAM
 E. ROLAND HARRIMAN
 ALBERT E. PARR
 Dean of the Council

CENTRAL ASIATIC PUBLICATIONS

ROY CHAPMAN ANDREWS, Chairman
 CHARLES P. BERKEY
 FREDERICK K. MORRIS
 LESLIE E. SPOCK

EMERITI

ROY CHAPMAN ANDREWS, Sc.D., Honorary Director
 BARNUM BROWN, Sc.D., Curator Emeritus of Fossil Reptiles
 JAMES P. CHAPIN, Ph.D., Associate Curator Emeritus of Birds; Research Associate in African Ornithology
 JAMES L. CLARK, D.Sc., Director Emeritus, Preparation and Installation
 WILLIAM K. GREGORY, Ph.D., Sc.D., Curator Emeritus of Fishes and Comparative Anatomy

E. W. GUDGER, Ph.D., Honorary Associate in Fishes and Librarian of Dean Memorial Library
 ROY WALDO MINER, Ph.D., Sc.D., Curator Emeritus of Invertebrates
 CHARLES C. MOOK, Ph.D., Associate Curator Emeritus of Fossil Reptiles
 NELS C. NELSON, M.L., Curator Emeritus of Prehistoric Archaeology
 WILLARD G. VAN NAME, Ph.D., Associate Curator Emeritus of Recent Invertebrates

SURVEY OF EXISTING KNOWLEDGE OF BIOGEOCHEMISTRY



3. *THE BIOGEOCHEMISTRY OF VERTEBRATE EXCRETION*

GEORGE EVELYN HUTCHINSON

Consultant in Biogeochemistry

The American Museum of Natural History

Professor of Zoology

Osborn Zoological Laboratory, Yale University

BULLETIN

OF THE

AMERICAN MUSEUM OF NATURAL HISTORY

VOLUME 96

NEW YORK:1950

BULLETIN OF THE AMERICAN MUSEUM OF NATURAL HISTORY

Volume 96, pages i-xviii, 1-554, text figures
1-103, plates 1-16, tables 1-56

Issued June 14, 1950

Price: \$10.00 a copy

To
GEORGE ALEXANDER KUBLER

PREFACE

THE "SURVEY OF CONTEMPORARY KNOWLEDGE OF BIOGEOCHEMISTRY" owes its existence to the generosity of Robert Earll McConnell and George Monroe Moffett, and to the imagination and foresight of Albert Eide Parr, Director of the American Museum of Natural History. The purpose of the survey is to bring together, and publish as a series of monographs, the available information on all aspects of the interrelation of biology and geochemistry. The contact area between these two sciences, which have only recently begun to influence each other, is of direct concern in many of man's efforts to cope with his environment. This is obviously true in agriculture, in the utilization of aquatic resources, in human and animal nutrition, and in certain branches of medicine. It is equally true that aspects of biogeochemistry are involved in our understanding of the history of the earth and its inhabitants, in fact whenever questions arise as to the origin, potentialities, and fate of mankind. In order to consider adequately both the details of practical importance and the more general principles of theoretical significance, all contributors to the series are asked to cast their nets widely, and to report whatever of interest they may find. Much of the information that is avail-

able in theory is published in such scattered, miscellaneous, and inaccessible works as to make it at present of very little utility. As such information is brought together, the interrelation of many previously disconnected facts becomes increasingly evident, and new generalizations emerge not previously available, because the facts known in theory were in practice never known by one and the same person.

The survey is intended as more than a synthetic summary. As much emphasis is to be placed on the lacunae in our present knowledge as on its established content. By defining the gaps carefully, a program for research is developing. Wherever well-defined problems can be investigated in the laboratory without prejudice to the development of the Survey, such studies are being made, but an enormous mass of uncertainty is bound to be disclosed without the prospect of any immediate investigation by those engaged in the project. It is, however, hoped that other workers will be attracted to the field by the inherent interest of the unsolved problems of biogeochemistry.

G. E. HUTCHINSON

*New Haven, Connecticut
August 18, 1948*

CONTENTS

PREFACE	xi
INTRODUCTION	1
GENERAL CONCEPTS AND TERMINOLOGY	3
Biological Conditions for Guano Deposition	4
Geophysical Conditions for Guano Deposition	5
GUANO DEPOSITS ON THE WESTERN COASTS OF THE CONTINENTS	9
Modern and Old Deposits on the Coasts of Peru and Chile.	9
Climatology and Oceanography.	9
The Peruvian Guano Birds.	14
The Position, Nature, and Importance of the Various Peruvian Islands	23
Conditions for the Formation of Old Stable Deposits	48
Periodic Fluctuations in the Bird Population of the Guano Islands	49
Qualitative Historic Changes in the Avifauna of the Guano Islands	58
The Chronology of the Peruvian Guano Deposits	65
Estimates from Modern Rates of Deposition	67
Estimates from Thickness of Stratification	68
Estimates from Archaeological Evidence.	69
Synthesis of Evidence on Chronology	69
Climatological Interpretation of the Chronological Conclusions	70
The Chemistry of Nitrogenous Guano.	71
Analyses of Fresh Excrement.	71
Analyses of Modern Guanoses Collected in Nature	72
Decomposition of Organic Nitrogen Compounds in Guano	75
Relation of Nitrogen to Phosphorus Contents of Guano	78
Analyses of Old Peruvian Nitrogenous Guanoses	80
Partial Analyses of Old Peruvian Guanoses	82
Relationship of Nitrogen to Phosphorus Contents of Old Peruvian Guanoses.	82
Alkaline Salts.	85
Sand Contents of Guanoses	85
Fluorine Contents of Guanoses.	85
Boron Contents of Guanoses.	86
Relation of Guano Production to Food Supply	86
Phosphatic and Leached Guanoses	88
The Mineralogy of Nitrogenous Guano	91
Ancient Nitrogenous Guano on the Coast of the Chilean Mainland	95
Description of the Coastal Chilean Guaneras.	96
Chemistry of Ancient Chilean Guanoses.	106
Chronological Remarks on the Chilean Coastal Deposits.	109
Inland Guano Deposits of the Atacama Desert	112
Elevated Ancient Guano on the Mejillones Peninsula	113
Minor Deposits in the Oceanic Part of the Peru Current and Elsewhere off the Western Coast of South America	120
Guano Deposits on the Coast of Lower California	122
Oceanography	122
Climatology	124
Ornithology	125
Total Production of Guano	126
Description of the Deposits	127
Supposed or Actual Guano Islands on the Pacific Coast of Lower California	127

Guano Islands Within the Gulf of California	129
Guano South of the Lower California Peninsula	133
Possible Inland Guano in Nevada, United States	133
The Southwest African Guano Coast	134
Climatology	136
Oceanography	136
Ornithology	139
Fluctuations in the Bird Population and in Guano Production on the South African Islands	142
Description of the Northern Islands	146
Chemistry of Guano from the Islands of the Northern Group	149
Description of the Colonial Islands	151
Chemistry of Guano of the Colonial Islands	152
Phosphatic Guano on the Northwest Coast of Africa	157
PHOSPHATIC GUANO ON THE ATOLLS OF THE PACIFIC OCEAN	160
Slightly Elevated Atolls of the Central Pacific	160
Oceanography	160
Climatology	163
Ornithology	164
Description of the Islands	167
Dry Islands Undergoing Phosphatization at the Time of Their Discovery	167
An Intermediate, Almost Unphosphatized Island	182
Wet Islands to the North	183
A Dry Island North of the Equatorial Rain Belt	186
Wet Islands to the South	186
Marginal Cases of Deposition in Fiji	187
Doubtful and Apocryphal Guano Islands	188
Atolls Without Phosphatic Deposits	190
Phosphatic Soil on Rose Atoll	191
The Total Quantity of Guano	192
Time Relations of Deposition	193
Climatic History of the Line and Phoenix Islands	194
An Atoll in the Eastern Pacific	195
The Hawaiian Leeward Islands	198
Oceanography	198
Climatology	198
Ornithology	200
Description of the Islands and Their Guano Deposits	202
Raised Phosphatized Atolls in the Tuamotu Group and Elsewhere in the South Pacific	208
Raised Phosphatized Atolls in the Equatorial Pacific (Ocean and Nauru Islands)	213
Raised Phosphatized Atolls and Other Islands in the Western Pacific	222
Phosphatic Deposits on Islands of the Purdy and Ninigo Groups, Admiralty Islands, and on the Schouten Islands	223
Phosphatized Islands in the Marshall, Caroline, Palau, and Mariana Groups, with Outlying Islands	227
Phosphatized Islands in the Borodino and Riu Kiu Groups and Other Localities South of Japan	236
The Borodino or Daito Islands	236
The Riu Kiu Islands	247
The Total Quantity of Phosphate on the Islands of the Western Pacific	250
Chronological and Climatological Remarks on the Phosphatized Islands of the Western Pacific	250

PHOSPHATIC GUANO IN AUSTRALASIA	253
Islands in the Coral Sea and off New Caledonia	253
Oceanography	253
Climatology	253
Ornithology	255
Description of the Islands	255
Islands off New Zealand and Other Localities on the New Zealand Coast and the Sub- antarctic Islands of New Zealand	260
Climatology	260
Oceanography	260
Description of the Localities	260
Islands in the Vicinity of Bass Strait and off Tasmania	264
Islands off the Central and Western Parts of the South Coast of Australia	267
Islands off the West Coast of Australia	270
Climatology	270
Oceanography	270
Ornithology	270
Total Quantity of Guano	270
Description of the Islands	271
Inland Avian Guano Deposits in Australia	274
GUANO ISLANDS IN THE SOUTH CHINA SEA, IN THE SEAS OF THE EAST INDIAN ARCHI- PELAGO, AND IN THE ADJACENT PARTS OF THE INDIAN OCEAN	276
Modern Guano Deposits	276
Climatology	276
Oceanography	276
Description of the Guano Islands	278
Ancient Phosphatization of an Elevated Coral Island	285
GUANO ISLANDS IN THE WESTERN INDIAN OCEAN AND ADJACENT SEAS	288
Rodriguez, Cargados Carajos, Seychelles, Amirante and Aldabra Islands, and Minor Madagascan Localities	288
Oceanography	288
Climatology	290
Ornithology and Biogeography	290
Description of the Islands	292
Seychelles Guano from Unspecified Localities	301
Total Quantity of Guano	302
Chronological Aspects of the Guano Deposits on the Islands of the Western Indian Ocean	302
Islands along the East Coast of Africa	303
Climatology	303
Oceanography	304
Ornithology	304
Description of the Islands	304
Islands in the Red Sea	306
Climatology	306
Oceanography	306
Description of the Islands	307
Islands on the Southern Coast of Arabia and Within the Persian Gulf	308
PHOSPHATIC GUANO ON THE ISLANDS OF THE ATLANTIC OCEAN AND ADJACENT SEAS	311
Islands of the Southeastern Tropical Atlantic	311

Islands of the Caribbean and Cayman Seas	315
Climatology	315
Oceanography	315
Ornithology	317
Description of the Islands	318
Islands in the Cayman Sea and the Western Reefs of the Caribbean	318
The Greater Antilles and Associated Islands	322
The Lesser Antilles	327
The Venezuelan and Dutch Leeward Islands	332
Chronological Aspects of the Guano Deposits of the Caribbean and Cayman Seas	344
Phosphatized Localities along the Northeast Coast of South America and in the Adjacent Ocean	345
Oceanography	345
Climatology	346
Description of the Islands with Contemporary Bird Colonies	346
Ancient Phosphatization on the Coast of Maranhão	348
Phosphatized Islands Off the Central Eastern Coast of South America	352
Islands of the Temperate South Atlantic and off Patagonia	353
The Patagonian Deposits	353
The Falkland Islands Deposits	357
GENERAL ASPECTS OF AVIAN GUANO DEPOSITION	360
Guano Deposition in the General Phosphorus Economy of the Earth	360
The Rate of Removal of Phosphorus from the Ocean by Sea Birds	360
The Total Quantity of Guano Deposited in Post-Pleistocene Time	361
The Total Quantity of Phosphatic Guano in Supposed Pleistocene Deposits	363
Climatic and Oceanographic Determinants of Guano Deposition	364
Relation to Precipitation	364
Relation to Upwelling	365
Biological Aspects of Guano Production	365
Taxonomic Status of the Guano Birds	365
Significance of the Size of Breeding Colonies	369
Changes in Terrestrial Biota Caused by Bird Colonies	369
Changes in Littoral Productivity Due to Bird Colonies	373
Paleoclimatic Conclusions	373
Significance of Phosphatic Deposits on Well-vegetated, Slightly Elevated Atolls; Possible Correlation with Changes on West Coast of South America	373
Phosphatic Deposits of Elevated Islands	376
CAVE GUANO	381
Cave Guano in South and Central America	382
Uruguay	382
Brazil	382
Venezuela	382
Honduras	384
Cave Guano in the Antilles	385
Puerto Rico	385
Hispaniola (Haiti and Santo Domingo)	388
Cuba	389
Jamaica	391
Bahamas	391
Cave Guano in North America (United States and Mexico)	393

Mexico	395
Texas	395
New Mexico	397
Miscellaneous Western Occurrences	401
Alabama	402
Missouri	402
Indiana	403
Tennessee	404
Other Occurrences in Eastern North America	405
Cave Guano on Pacific Islands	405
Mariana Islands	405
Cave Guano in Australia and New Zealand	406
Victoria	406
New South Wales	408
South Australia	409
West Australia	410
New Zealand	410
Cave Guano in Tropical Asia	410
New Guinea	410
New Ireland	410
Borneo	410
The Philippine Islands	412
Java	412
Sumatra	413
Indo-China	413
Malay States	414
Burma	418
Cave Guano in Africa	418
South Africa	418
Central Africa	419
Madagascar and the Mascarene Islands	421
Madagascar	421
Réunion	421
Egypt	422
Palearctic North Africa	422
Cave Guano in Europe	423
Yugoslavia	426
Rumania	427
Hungary	429
Austria	431
Czechoslovakia	441
Poland	443
Germany	443
France	444
The Iberian Peninsula	451
Islands in the Western Mediterranean	452
Peninsular Italy and Sicily	456
Great Britain	457
Note on Album Graecum or the Fossilized Dung of the Cave Hyena, <i>Hyaena</i> <i>crocota spelaea</i>	458
General Aspects of Cave Guano	459
The Relationship of Nitrogen to Phosphorus	459
The Decomposition of Nitrogen Compounds	460

The Copper Contents of Bat Guanos	461
THE COMPARATIVE GEOCHEMISTRY OF GUANO MINERALS	462
Water-soluble Minerals	462
Oxalates	462
Sulphates	463
Nitrates	463
Phosphates	464
Bicarbonate	464
Calcium Phosphate Minerals	464
Brushite and Monetite	464
Whitlockite and Martinite	466
The Apatites	467
Substitutions Involving the Halogens	468
Substitutions Involving Calcium	468
Substitutions Involving Phosphorus	469
The Problem of the Carbonate Apatites	469
Tricalcium Phosphate Hydrate	469
Nomenclature	469
Collophane and the Colloidal Calcium Phosphates	469
The Apatites of Insular Phosphate Deposits	470
Fluorine in Insular Phosphates	470
Other Halogens in Insular Phosphates	473
Substitutions for Calcium and Phosphorus	473
Magnesium Phosphate Minerals	474
Aluminum and Ferric Phosphate Minerals	475
Minerals of Composition $(\text{Al,Fe})\text{PO}_4 \cdot 2\text{H}_2\text{O}$ Associated with Insular Phosphatization	475
Minerals Formed by Inland Epigeal Phosphatization in Australia	477
Other Aluminum and Ferric Phosphates Formed under Tropical Epigeal Conditions	478
Epigeal Formation of Taranakite	478
Hypogeal Formation of Taranakite and Other Aluminum Phosphates	479
SUMMARY OF PREVIOUSLY UNRECOGNIZED CONCLUSIONS	481
BIBLIOGRAPHY	483
INDEX	521

INTRODUCTION

THIS WORK, THE THIRD MONOGRAPH to appear in the "Survey of existing knowledge of biogeochemistry," is devoted to the study of the concentration of certain widely diffused elements, notably nitrogen and phosphorus, in deposits formed as the result of the excretory activities of animals. The greater part of the material to be considered relates to the guano deposits formed by sea birds. A special difficulty is inherent in the nature of this subject, namely, that virtually all the important guano deposits were quarried away during the nineteenth century without any adequate account of their nature being prepared. Such information as was recorded is moreover scattered through a great mass of the most miscellaneous literature, trade pamphlets, agricultural journals, political documents, and books of travel. The work of preparing the present account has therefore presented problems more familiar to the historian than to the naturalist. Many of the primary sources show indications of bias owing to commercial interests, and in one or two cases the question of the authenticity of a document has arisen.

Though the adventures of whaling captains, the political significance of the skull of the last male Tasmanian, the sidelong glances of the Peruvian *tapadas*, the black and white butterfly that lured Saint Rose of Lima into the Dominican Order, and other curiously colored tales have played their part in relieving the tedium inherent in the study of much seemingly unpromising material, the greatest help has come from various friends who have put their knowledge freely at my disposal.

To Prof. George A. Kubler of the Department of the History of Art of Yale University I owe a special debt of gratitude, for without his assistance the most interesting results of the present study would never have been achieved. Apart from his special archaeological contribution, permitting a new approach to the chronological problem presented by guano deposits, his extraordinary knowledge of the literature of South American history, topography, and travel has been of immense assistance.

It is also a pleasure to acknowledge the

help given by Dr. Robert Cushman Murphy, whose beautiful "Oceanic birds of South America" has been my literary companion since the inception of this work, and who has put his experience and material freely at my disposal. I am particularly grateful to him for the extended loan of certain old photographs of great importance.

Dr. William Vogt of the Pan-American Union, whose studies have done so much to illuminate the problems of guano production on the South American coast, has made available a microfilm of the manuscript of his most important work, enabling me to check errors in the published version, and has most kindly read that part of the present work relating to the South American coast. Mr. C. Bernard Lewis has likewise read the section on the Greater Antilles and has given me valuable information.

The expert knowledge of a number of my colleagues in Yale University, Dr. S. C. Ball, Dr. V. T. Bowen, Prof. Richard Foster Flint, Dr. E. M. Low, Dr. G. A. Riley, Dr. John Rodgers, Dr. George Switzer, Dr. E. F. Thompson, Mr. Alexander O. Viator, and Dr. Horace Winchell, has been of great assistance in discussion of ornithological, geochronological, mineralogical, oceanographic, and maritime matters. Prof. Paul F. Kerr of Columbia University has provided material of importance in solving certain problems of guano mineralogy, and Mr. F. A. Bannister of the British Museum (Natural History), London, has collaborated in the study of the most interesting of these problems. Dr. Sidney C. Hsiao has helped with translation from the Chinese, and through the good offices of Dr. S. Dillon Ripley, Dr. Harold Coolidge, Capt. W. F. Jennings, and Dr. John Rodgers, translations of the important Japanese works of Aso and Yamanari have been available.

I am also much indebted to Dr. Enrique Avila, Ornithologist to the Compañía Administradora del Guano, Lima, Peru; to the firm of Geo. W. Beermaker, Inc., San Diego, California; to Sr. Carlos H. Benítez, General Manager of Guanos y Fertilizantes de Mexico, S. A.; to the British Phosphate Commissioners of London and Melbourne; to Mr.

S. W. Boggs of the Department of State, Washington, D.C.; to the Chamber of Commerce, Havre de Grace, Maryland; to Dr. W. E. L. H. Crowther of Hobart, Tasmania; to Mr. Carl C. Cutler of the Mystic Marine Historical Society, Mystic, Connecticut; to Mr. Llewellyn Howland of South Dartmouth, Massachusetts; to Mr. Frederick C. Noyes, Executive Secretary of the Phosphate Export Association; and Mr. William Williams of New York City, who have answered my somewhat minute inquiries in detail and have provided various otherwise inaccessible facts or indications of unsuspected sources of information.

Permission to copy figures is gratefully acknowledged from the following: Allan Hancock Foundation for Scientific Research, University of Southern California; American Geographical Society; American Philosophical Society; Australian Museum, Sydney, Australia; British Ornithologists' Union; Coal Age; Compañía Administradora del Guano, Lima, Peru; Dirección general de Minas y Geología, Argentina; Discovery Committee, Colonial Office, London; Editor, Archives de Zoologie Expérimentale et Générale, Paris; Geological Society, London; Geological Survey, Union of South Africa; Mr. E. H. Bryan, Jr., and the Tongg Publishing Company, Honolulu; Sir A. F. Ellis and Messrs. Angus and Robertson Company, Sydney, Australia; Mineralogical Society of America; New York Zoological Society; Peabody Museum, Yale

University; Revista Chilena de Historia y Geografía, Santiago, Chile; Sears Foundation; Southwest Museum, Los Angeles; United States Department of the Interior, Fish and Wildlife Service; United States Hydrographic Office; and the United States National Museum.

The never-failing help of the reference staff of the Sterling Memorial Library of Yale University has greatly lessened the bibliographic difficulties of the subject, and it has been my peculiar fortune to have available at Yale the riches of the Hiram Bingham collection of Latin Americana in which a number of South American works were discovered that one would ordinarily hardly dare hope to find even in the richest North American libraries. It is also impossible to avoid paying tribute to the subject index of the New York Public Library, without which a number of obscure but highly important works would have been missed.

The skilful help of my assistants, Mrs. Jane K. Setlow and Miss Ruth J. Jaffe, has contributed greatly to all aspects of the work, while Miss Lisbeth Krause and Mrs. Georgiana B. Deevey have taken great care in the preparation of the figures.

As always, I owe a deep debt of gratitude to my wife, who, *inter alia*, has, by her literary intuition, rescued me from one very serious mistake in preparing the present study.

GENERAL CONCEPTS AND TERMINOLOGY

IN THE MOST GENERAL TERMS, elements that are dispersed in the biosphere may undergo biological concentration not only in the bodies of organisms and in their dead remains, but also in their excretory products. Since a well-developed excretory function is characteristic of animals but not of plants, all such excretory concentrates are the result of a process occurring in several stages, only the last of which involves excretion. The initially dispersed elements are first collected in the bodies of plants, some of which are eaten by animals, a part of which may in turn be eaten, and so on. At some level in this food chain, the excreta, often mixed with egesta, instead of undergoing bacterial decomposition and rapid restoration to the cycle of the elements, may accumulate in such large quantities that they constitute a geochemically significant deposit. Such a deposit may contain specific minerals and may react in specific ways with the rocks with which it is in contact. Accumulated excreta and egesta of this kind are conveniently termed guano, a word derived from the Quechua *huanu*,¹ meaning dung, and first applied to the enormous deposits of bird droppings found on the Peruvian coast. The term will be used to imply a localized accumulation of excreta and egesta² or their derivatives, containing material concentrated from over a wide trophophoric field³ onto a relatively restricted resting or breeding site. The coprogenic sediments, common in lakes or shallow seas, are thus excluded from the definition because they are produced by animals which feed, excrete, and defecate in one place. The true excreta of such animals probably seldom accumulate, though little is

¹ Though the spelling with an initial aspirant is more correct, *guano* and its derivatives *guanera* and *guanay* are more familiar than the alternative phonetic *huanu*, *huanera*, and *huanay*, and so will be used throughout except in quotation.

² Vertebrate feces probably always contain excretory matter as well as undigested material that has, topologically, never been within the organism. The inclusion of mammalian fecal deposits as guano therefore does not strain the definitions unduly.

³ Wheeler (1928); there is no need to limit this useful term, for the area over which a localized animal colony collects its food, to the social insects.

known about intestinal excretion in the species producing coprogenic sediments.

It may be necessary on occasions to distinguish between the deposits produced by different kinds of animals by use of terms such as bird guano, sea-lion guano, or bat guano, but in general the origin of the material will be clear from the context.

The word *guanera*, in common use in Peru, will be employed to indicate a guano deposit as a geographical entity.

An arbitrary use of the adjectives old and ancient has proved convenient. The term old guano is reserved for the material of unexploited deposits which remained sites of deposition up to the time that guano diggers began operations. The term ancient guano is defined as guano from a *guanera* deserted by the producing organisms at a relatively remote, though apparently usually post-Pleistocene, date. In contrast to these terms, modern guano is material deposited by contemporary colonies, usually on exploited sites from which old guano has been removed; such modern guano is often collected as a fertilizer at intervals of a few years.

It is customary to distinguish between nitrogenous guano, containing a large part of the nitrogenous organic matter of the original excreta, and phosphatic guano in which the organic nitrogenous fraction has been lost, leaving a material that usually consists of calcium phosphate minerals. The term leached guano is properly limited to those cases in which phosphatic guano has been formed by percolating water. The result of this process is not merely a loss of easily soluble salts and a decomposition of organic nitrogen but, owing to the incongruent solubilities of all calcium phosphates save those of the apatite series, a loss of phosphate ions also. When decomposition occurs in damp air but losses are due solely to volatilization of decomposition products, and not to transport of the lost material in aqueous solution, the term decomposed guano is appropriate. The number of cases in which a valid distinction can be made between leached and decomposed phosphatic guanos is, however, very limited.

Guano as here defined is not the only excretory product of geochemical interest. In many formations, discrete fossil fecal masses or coprolites are found and may represent in aggregate quite significant accumulations of phosphate. The problems presented by coprolites are somewhat different from those presented by guano and will not be considered in the present work.

Guano deposits are formed only when the organisms producing excreta are relatively large, feed over a wide trophophoric field, and return to a limited site for rest or reproduction. These, though necessary, are not sufficient conditions for the production of a

deposit, for certain geophysical requirements must also be met. In general the geophysical conditions to be expected are that the substratum must be of a suitable form to retain the deposit and that the rainfall must not be so great that the deposit is entirely washed away. The biological and geophysical conditions are, however, not entirely independent, for in the case of guano produced by marine birds, the same factors that make the regions of the richest guaneras arid also provide that the adjacent seas be unusually fertile, permitting an extraordinary quantitative development of the marine biota and extraordinary populations of marine birds.

BIOLOGICAL CONDITIONS FOR GUANO DEPOSITION

The biological conditions appear to be fulfilled almost exclusively by vertebrates. The use of the soil of certain termite nests (summary in Pax, 1938) and possibly also of ants' nests (Chandos, 1945)¹ as fertilizer may point to an analogous phenomenon among social insects, but these animals are not very much larger than the soil particles, sand grains, and fragments of plant debris of which the nest is constructed so that their excreta never form recognizable discrete deposits, even though it is fairly certain that each colony must be a center of concentration of the elements of the food brought in from outside.

Among the vertebrates only the birds and mammals have attained a degree of nervous and psychological complexity required for the full development of the colonial habit. The birds moreover have a peculiar biochemical advantage over the mammals as guano producers, in that they excrete a semi-solid urine in which the main nitrogenous compound is uric acid, a rather stable and insoluble substance (uricotelic metabolism), whereas mammals produce a liquid urine, in which the main nitrogenous compound is urea (ureotelic metabolism), an unstable and soluble substance.

The uricotelic type of nitrogen metabolism is, as Needham (1931) has stressed, charac-

teristic of those animals that develop in eggs closed off from the environment. It is supposed that in such cleidoic eggs the accumulation of freely diffusible urea would be a biochemical inconvenience to the embryo, and that once a mechanism for synthesis of uric acid is developed it is retained throughout life. The reptiles share uricoteliosis, as well as many other characters, with the birds, and though reptilian guano is unknown, the production of coprolites has frequently been attributed to reptiles, and it is possible that uric acid plays a part in the fossilization of such bodies.

Among the birds the development of large localized colonies feeding over a wide trophophoric field is obviously facilitated by the development of flight, which makes possible a more complete exploration of the area around the colony than would be possible for a purely terrestrial animal. While such colonies are not confined to marine species, it is evident that the sites of colonies of sea birds can most generally meet the geophysical limits imposed on guano accumulation, namely, the coexistence of a highly productive trophophoric field and a dry area to provide the necessary solid substratum for reproduction.²

² Though Cardan learnedly has it that the Paradise bird lives wholly in the upper air, the need for a solid substratum in reproduction is doubtless the limiting condition that prevents the development of a completely aerial animal once soaring flight has been evolved. If some of the pterodactyls were viviparous they may have whelped on the wing, but no authority on these extinct animals seems to have taken this hy-

¹ This charming work mentions the alleged fertilizing properties of material from the nests of certain Mexican ants, but the distinction between ants and termites is not always made in popular writing.

Such conditions are obviously satisfied by the coexistence side by side of a fertile seascape and a barren landscape. There are, however, a few cases known in which similar conditions have been provided in the past by lakes in semi-arid regions (pp. 133, 275) and apparently one case (p. 274) where the long-continued occupation of a rock in a dry landscape by a few birds has permitted the accumulation of significant amounts of phosphate of excretory origin in fissures and cavities.

Not all colonial sea birds produce guano. Significant deposits are known to have been formed by colonies of penguins (Sphenisciformes), albatrosses and perhaps diving petrels (Procellariiformes), and terns (Charadriiformes), but it is probable that all these deposits are small compared with those produced by a relatively few species of Pelecaniformes, namely, certain pelicans, boobies, and cormorants. These birds appear specially prone to deposit the greater part of their droppings on the colonized land area; evidence given below (p. 87) very strongly suggests that this is not accidental but a definite feature of the behavior of the bird. In the breeding season the material is used in nest construction.

In contrast, the marine Charadriiformes, notably the gulls, seem as adults not to deposit a disproportionate quantity of their droppings on the breeding ground and possi-

bly even avoid fouling the area to some extent. Only one doubtful case of a gull producing guano is known. Among the terns, *Sterna fuscata* and a few other species are apparently guano birds, but some authors seem doubtful of their significance as really effective guano producers, and it is possible that where they have formed impressive deposits, time and the immense sizes of some of the colonies are responsible.

Among the mammals two groups provide a formal parallelism to the guano birds. The first group is that of the seals, which often live with the guano birds and which, coming on land to breed, frequently produce small deposits of seal guano. This material is, however, primarily fecal and low in nitrogen. The second group comprises cave-living bats, which may form immense colonies. Here the trophophoric field is a terrestrial one, and the guano deposit is produced solely because the bats rest in aggregates in cavities in which little contaminating material can accumulate and from which, if the cave is dry, little material can be carried away. The material is a mixture of feces and urine, but the urea of the latter easily decomposes, and such of the resulting ammonia as is not lost is not infrequently nitrified. Most of the nitrogen that can be retained is, however, probably in the form of chitin. A very few cases of cave deposits formed by wholly terrestrial mammals are known.

GEOPHYSICAL CONDITIONS FOR GUANO DEPOSITION

The best substrata appear to be provided by flat islands. Most of the large colonies of sea birds are insular, probably owing to the freedom from attacks of predaceous mammals that results from the choice of such habitats. It is worthy of notice that New Zealand, which lacked a native terrestrial mammal fauna, provides the only known case of a true gannet (*Morus serrator rex* Mathews and Iredale) colony on a headland rather than an island. No general geographical rules can be established to describe the

pothesis seriously. Man, since he can carry his *nidus* with him, could liberate himself from this restriction, but it is difficult to see any reason which would prompt him to complete his fetal life and enter the world on an air liner.

insularity of a coast line, but abundant examples of its importance will appear throughout the work.

The oceanographic and meteorological conditions are more amenable to deductive treatment. In an ideal ocean, bounded by continental coast lines running from high northern latitudes to a point about 40° S. and opening into a circumpolar Antarctic ocean, a system of currents will be developed that is fairly well approximated by the actual current pattern of the Atlantic and Pacific oceans (fig. 1). In the latitudes of the trade winds, the main surface currents will be the North and South Equatorial Currents flowing to the west. In the higher latitudes of the

westerly winds, the main surface water movements will be currents flowing to the east. Ideally the circulation will be completed by longitudinal currents flowing from low to high latitudes on the western side of the ocean, and from high to low latitudes on the eastern side. In conformity with the general theory of currents, the water of high density, that is, of low temperature, will be on the

the general disposition of the land masses accentuates the longitudinal component in wind direction, as is often the case, so that the wind tends to follow the coast from high to low latitudes, just as the current would in the absence of wind, the current will tend to move out to sea, owing to Coriolis forces. Strong unilateral divergences may therefore be expected along the western coasts of the

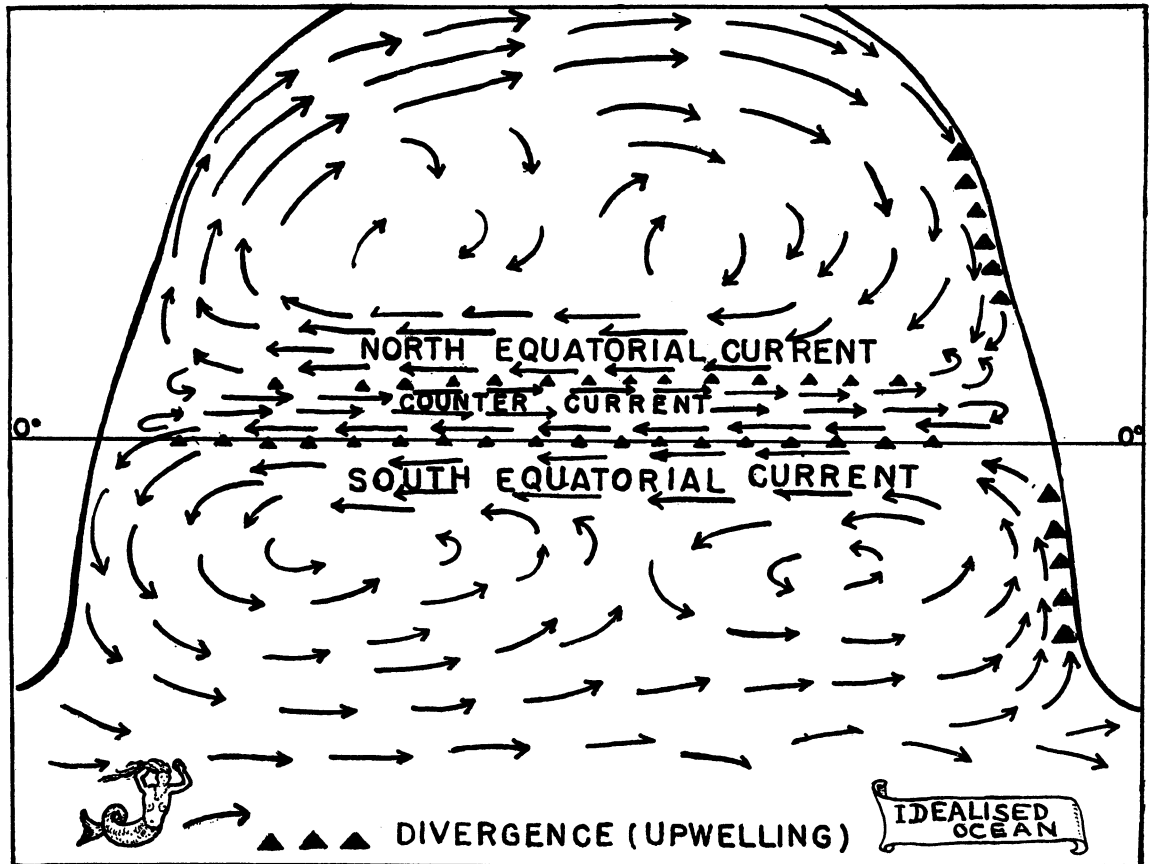


FIG. 1. General diagram of the surface circulation and distribution of upwelling in an idealized ocean bounded by approximately longitudinal continental coast lines.

coastal side of these currents. In the latitudes of the trade winds, there will be a tendency for water to be moved from east to west, and this will be in part compensated not only by the northward movements of the coastal currents constituting the eastern limbs of the gyral but also by the drawing up of water from below the surface along the eastern margins of the oceanic basins. Moreover if

continents, and considerable upwelling of cool subsurface water rich in nutrient salts will mark these divergences. Most of the early part of the present work is devoted to a study of the consequences of this type of hydrographic pattern.

Between the two Equatorial Currents running to the west a counter current is developed. According to Montgomery (1941)

this Equatorial Counter Current is due primarily to the piling up of water by the trade winds on the western sides of the oceanic basins. The water tends to flow back eastward in the intervening belt of equatorial calms which is known to mariners as the Doldrums. This zone, and the Equatorial Counter Current, lie, owing to the disposition of land masses and the consequent northward displacement of the meteorological Equator, somewhat north of the geographical Equator. It has been shown theoretically that frictional forces must produce marked

Equator within the South Equatorial Current. The original demonstration of such a circulation pattern was theoretical, due to Defant (1936), and was based on friction due to vertical mixing. There are now adequate observational data that confirm Defant's conclusions, though Sverdrup (Sverdrup, Johnson, and Fleming, 1942) believes that the system is due to friction set up by lateral rather than vertical mixing as postulated by Defant. The general pattern of great transoceanic divergences and convergences brought out by the available data is of immense im-

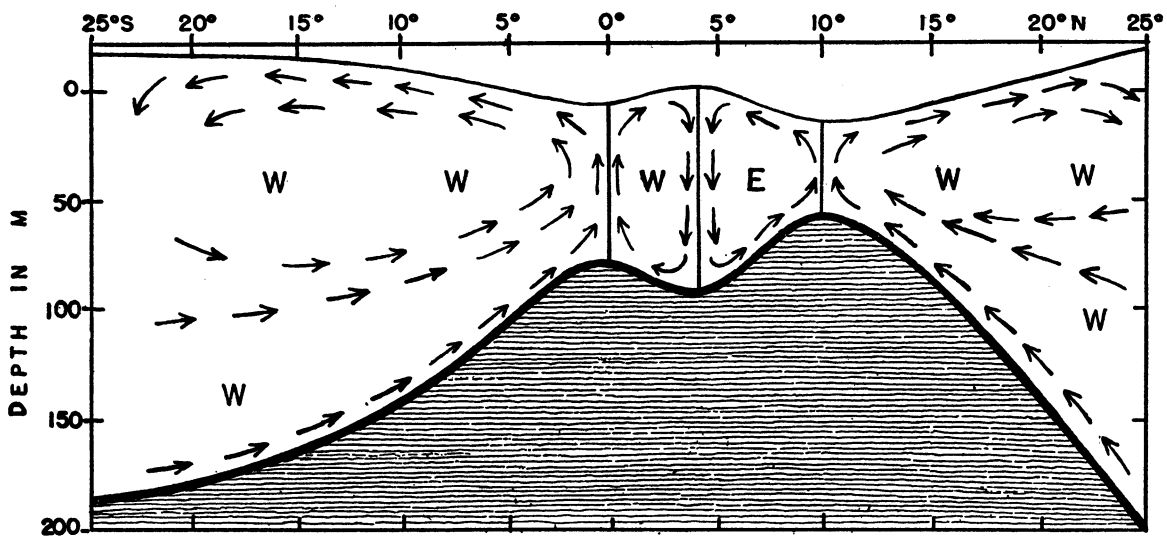


FIG. 2. Circulation pattern in a transverse section of the equatorial region of an idealized ocean. After Defant.

lateral or rotatory movements in such a current system (fig. 2). The result of such forces is to produce a movement of water from north to south at the surface of the counter current and from south to north in the adjacent regions of the two equatorial currents. In the North Equatorial Current such a movement corresponds to the general rotation, but in the South Equatorial Current it does not. The part of the South Equatorial Current to the north of the Equator therefore forms a long cell rotating in an opposite sense to the Counter Current or to the rest of the South Equatorial Current. In consequence two divergences are set up, one on the boundary between the North Equatorial Current and the Counter Current, the other on the

portance in biological oceanography. Much of the middle section of the present work is an exposition of the apparent consequences of this type of hydrographic pattern in the central Pacific Ocean.

At higher latitudes in an ideal ocean there would be a good deal of vertical transport, particularly in the circumpolar Antarctic ocean where it is known that a great deal of such movement must occur just north of the Antarctic convergence. In general there is a very close relationship between such vertical mixing and the biological productivity of the ocean. Accordingly it is found that the whole region just north of the Antarctic convergence is extremely rich in living organisms. This region and the more complex northern

regions of equivalent latitude are, however, largely irrelevant to the present study.

The latitudes of the Doldrums, about the meteorological Equator, will tend to have heavy adiabatic rainfall, while in the latitudes of the trade winds there will be heavy precipitation only where the winds impinge on the eastern sides of bold continental relief. Local and seasonal conditions modify this simple pattern, but in general the great deserts of the world lie in subtropical latitudes, and the western coasts of the continents tend in these latitudes to be drier than the eastern.

The dry areas of the western coast lines thus correspond in general to the regions of upwelling on the landward sides of the currents flowing towards low latitudes, and the cold upwelled water accentuates this aridity by insuring that such air as moves from over the cold sea onto the hot land is warmed in the process and cannot deliver as rain the water vapor that it may carry, though fog over the cold coastal waters is a characteristic feature of the meteorology of such regions. The dry subtropical western coasts are thus the ideal regions in which sea birds can find abundant food and deposit their guano where it will suffer little decomposition.

The relationship of the far less well-known and less impressive central oceanic equatorial divergences to the equatorial rain belt is by no means so clear. Too little data are as yet published on central Pacific oceanography to permit a full understanding of the problem. At the present time the equatorial rain belt lies at about the southern edge of the counter current, north of the geographical Equator

and of the southern divergence, which thus falls in a dry zone. The region of the northern divergence on the northern edge of the counter current is seemingly drier than is the region of convergence on the southern edge of the counter current. The southern divergence is probably the more important, and numerous guano islands are associated with it, but it is hardly possible to predict deductively at present what changes would occur if the thermal Equator moved nearer to the geographical Equator, or crossed to the southern side. This matter will be considered more empirically below.

For the other parts of the earth's surface local conditions are probably always more important than the effects of the generalized planetary circulation that has been outlined. Accordingly the present work has been planned to consider first the regions of the western coasts of the Americas and of Africa, beginning in each case with the Southern Hemisphere, then to proceed to the central Pacific where the equatorial pattern of upwelling is best developed. The rest of the world is then considered, passing westward from the Pacific through Australasia and the Indian Ocean to the central Atlantic islands and ending in the Caribbean region. After this geographical presentation of the relevant data it is possible to proceed to certain more general topics and to a discussion of the analogous phenomena on land. The geochemical processes that have been discussed in relation to single localities are then summarized, and finally a brief statement of the principal new conclusions of the work is given

GUANO DEPOSITS ON THE WESTERN COASTS OF THE CONTINENTS

MODERN AND OLD DEPOSITS ON THE COASTS OF PERU AND CHILE

CLIMATOLOGY AND OCEANOGRAPHY

THE COASTS OF PERU AND NORTHERN CHILE, on the islands of which nitrogenous guano can accumulate, are climatically and oceanographically peculiar. The interrelations of the climate and oceanic circulation are so intimate that no attempt will be made to separate them, and the peculiarities of both will be summarized together.

It has long been known that the waters off the guano coasts are much colder than would be expected from their latitudes. After the initiation of serious scientific study of the region by von Humboldt, it was generally held that a cold coastal current ran northward along the whole South American coast from very low latitudes to about 5° S. Later works have demonstrated clearly that the cold water could not possibly be derived from Subantarctic water and that the only possible origin of such cold water is by upwelling. Modern studies, culminating in the excellent works of Schott (1931), Gunther (1936), and Schweigger (1940, 1943), have revealed a situation of considerable complexity.

The fundamental surface current system of the region constitutes the eastern limb of the great southern anticyclonic circulation system of the southern Pacific. In the latitudes under consideration, several hundred miles out to sea, the main current sets northwest, swinging round to form the westward flowing South Equatorial Current. Far out to sea the normal wind direction is from the southeast, as is to be expected in the latitudes of the trade winds. Near the coast the wind direction is largely determined by the presence of the Andes, which are high enough to cut off the troposphere over the eastern Pacific from the rest of the circulating atmosphere in the same way that South America cuts off the Pacific Ocean from the Atlantic Ocean. Wind direction therefore tends to follow the coast line very closely. Local reversals and irregularities may be noted, but in general the direction is from the south on the Chilean coast and from the

southeast on the Peruvian. The wind thus blows along the eastern edge of the South Pacific Gyral, the direction of which is itself determined by the form of the coast line. Two factors will now operate to produce upwelling. First, the current will tend, according to the Ekman law, to turn to the left of the wind, that is, to diverge from the coast. Second, the general movement of water to the northwest or west out to sea, in the northern part of the region under consideration, will tend to aspirate water from the coast. Schott emphasizes the first of these mechanisms, Gunther the second; both doubtless are important.

The simple conception of a single stream moving northward and rotating outward from the coast is, however, an inadequate picture of the situation. The Peru Coastal Current, as Gunther terms it, varies greatly in velocity from place to place, and local reversals are known. Thus Gunther noted no current off Callao, and Schweigger (1940) states that a current from the north flows towards the Chincha Islands and enters the Bay of Pisco (fig. 6). Vogt, however, found little or no evidence of this. It is certain that there is a tendency for tongues of warm water to be drawn southward and in towards the coast in compensation for the outward and northward movement of cold upwelled water. These tongues produce, with the cold water moving northwest, a series of anticyclonic swirls. Gunther concludes that there is normally one such swirl with its center at about latitude $6^{\circ} 30'$ S. off the Lobos Islands and another off San Juan with its center at about latitude 15° S. (fig. 3). Three more are probably developed along the Chilean coast. Schweigger's results, summarized in his map here reproduced (fig. 4b), indicate a more numerous set of interdigitating tongues of warm and cold water. He believes, moreover, that Gunther was in error in regarding the warm limbs of his two swirls as definite large counter currents originating far out to sea. Further work on this matter is clearly needed.

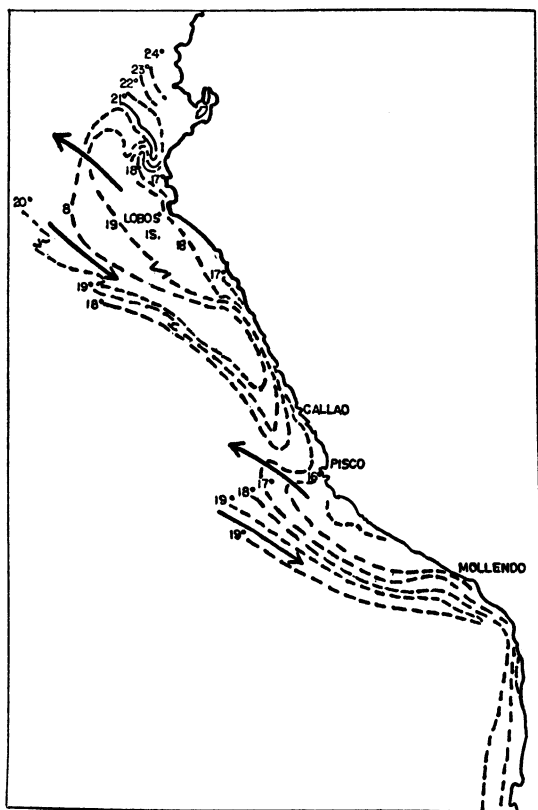


FIG. 3. The structure of the Peru Coastal Current. After Gunther.

During the winter the coldest water encountered in the regions of the greatest upwelling is slightly over 14°C . Persistence of water of under 15°C . for many weeks is regarded by Schweigger (1940) as abnormal and may have unfavorable local biological effects. Schott's general map (fig. 5a, b) for August and September indicates the water off the entire Peruvian guano coast to lie between the isotherms 15° and 17°C ., while in February and March the water of the same region normally lies between 19° and 20°C . when passing from the coast out to sea. Schweigger regards 22°C . as the upper limit for dark green coastal water, 23° to 25°C . the lower limit of full oceanic blue. Over the cool water the relative humidity is higher than over the warm oceanic water; in the winter, mist and drizzle (*garua*) are common, but true rain virtually never falls, since movement of cool, damp, oceanic air onto the

coast inevitably is accompanied by a rise in the temperature of such air.

The upwelling water is, as might be expected, rich in phosphate and presumably in other nutrient salts. The isostere for 80 milligrams of P_2O_5 per m^3 is seen in many of Gunther's sections to run up to the surface near the coast, and in general he obtained evidence of increased phytoplankton and increased phosphate in the upwelled waters. He also found, as is to be expected, that massive phytoplankton crops were associated with low phosphate within the upwelled zone and calculates that in water unequivocally of such origin up to 57% of the phosphate may be used by the phytoplankton. Gunther concludes that the mean maximal development of phytoplankton is from 6 to 8 kilometers (4–5 miles) from the shore, though there was a second peak in the region from about 90 to 160 kilometers off shore, probably due to inadequate sampling. There appears to be a strong tendency for heavy phytoplankton to be limited to certain special patches of water, presumably determined by the specially strong upwelling produced by the cold tongues of anticyclonic swirls. Schweigger, however, concludes from observations of the usual positions of concentrations of shoals of fish, that the most productive regions are just inside the landward ends of the warm tongues, where he supposes small subsidiary eddies are formed (fig. 6).

Vogt (1942) found transparency greater off the Chincha Islands in winter than in summer and concluded that this is due to greater phytoplankton production in summer. There seems to be a tendency for transparency to fall after temporary falls in temperature during the summer, owing no doubt to discontinuous access of upwelled water producing temporary increases in the plankton population.

The situation summarized above is that of so-called normal years; not infrequently abnormal conditions are observed. These are apparently to be referred in general to the abnormal approach of warm water to the coast. When this happens the condition locally termed *aguaje* intervenes. A number of different types of *aguaje* are recorded; the most spectacular types are characterized by

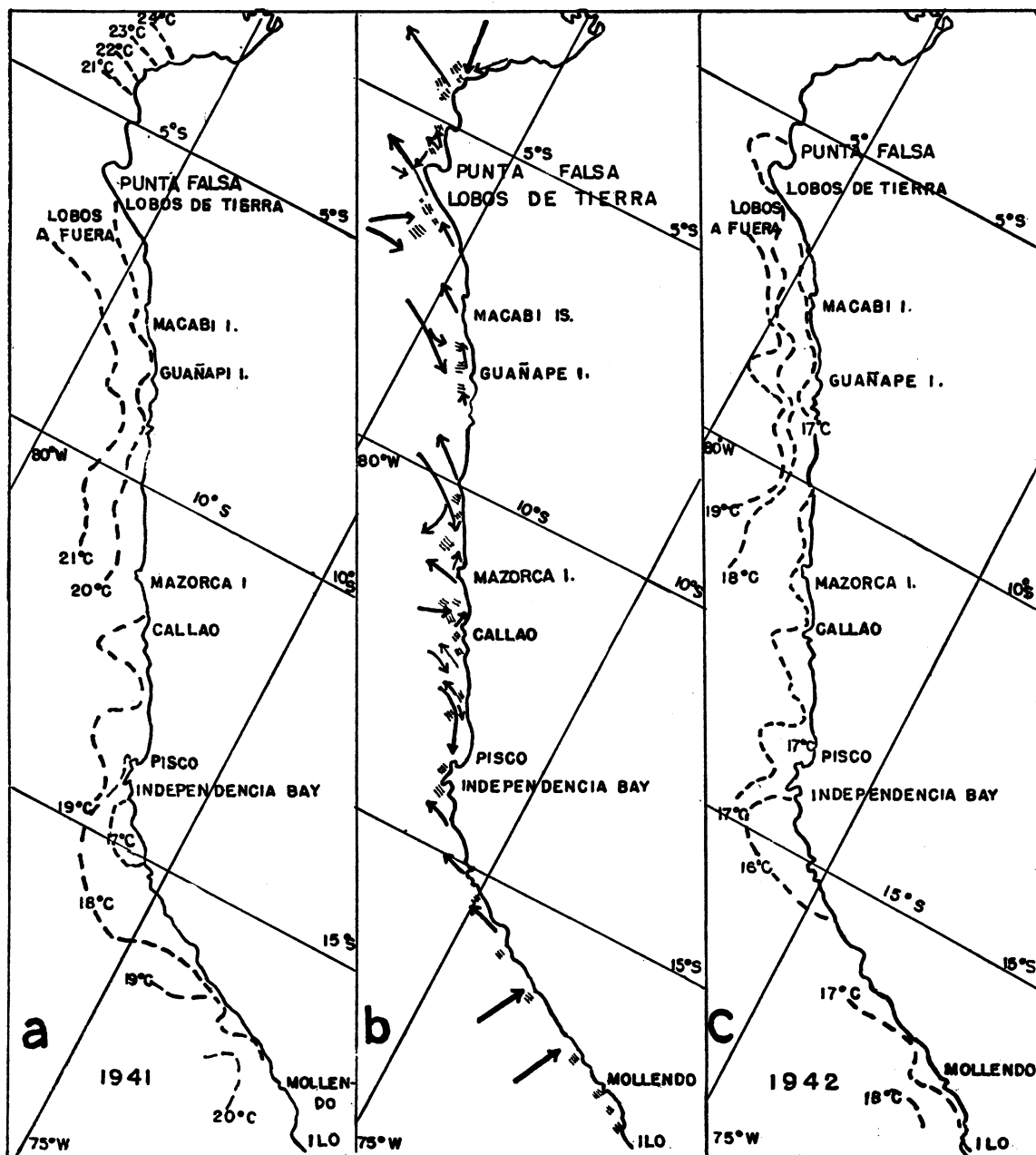


FIG. 4. The mean temperature distributions and current structure in the Peru Coastal Current. A. Temperature, 1941. B. Supposed circulation pattern. C. Temperature, 1942. After Schwiegger.

abnormal red, yellow, or brown coloration, death of marine organisms, and production of hydrogen sulphide. The last-named substance darkens the white paint of ships and so is responsible for what mariners term the Callao Painter or El Pintor. Abnormal colors

are presumably in part due to abnormal phytoplankton blooms. Aguaje can apparently occur locally at any time of year. Gunther reasonably attributes it to temporary convergence of the warm tongues of the swirls with the coast. The most spectacular cases of ab-

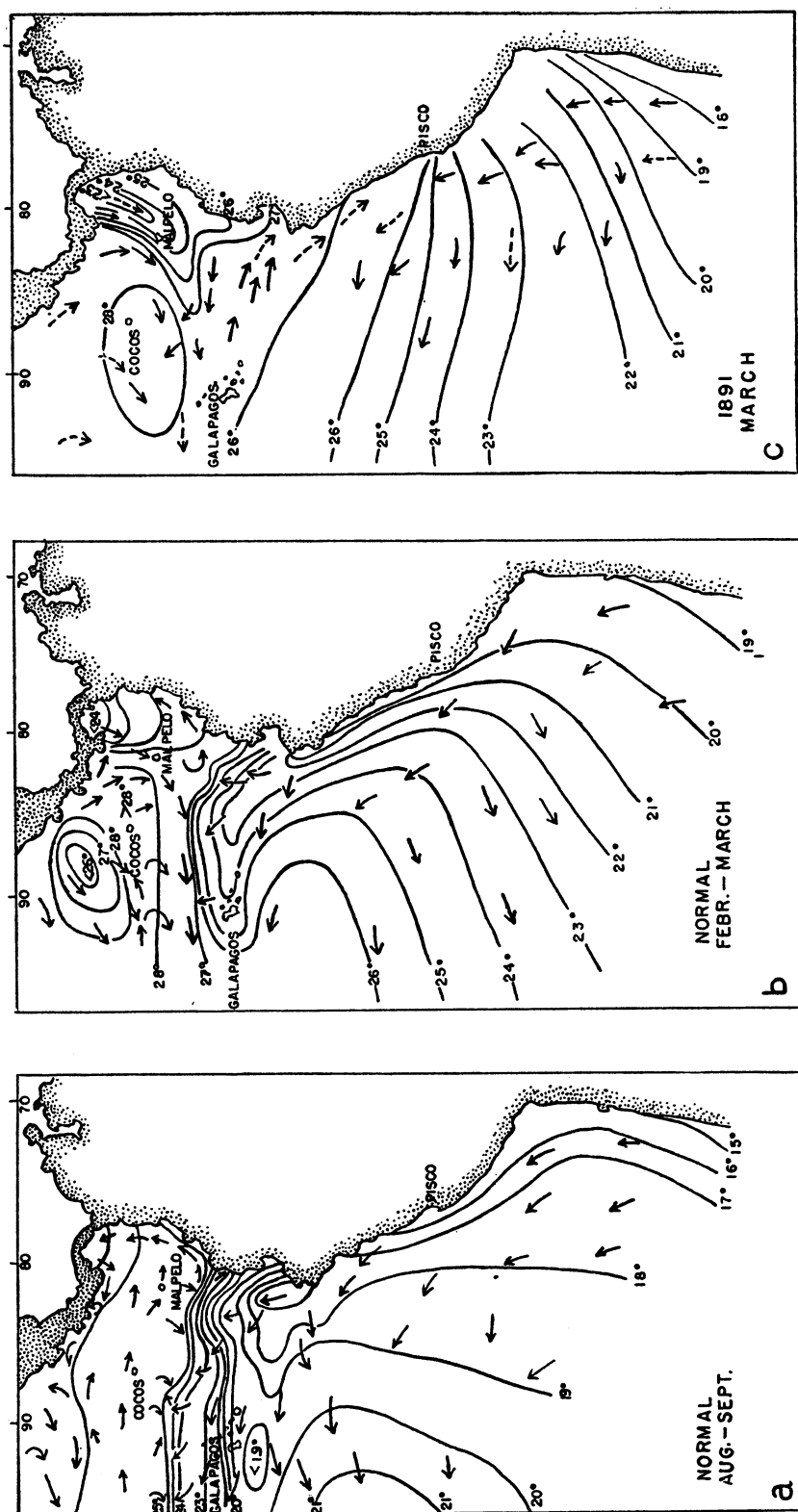


FIG. 5. Distribution of surface temperatures off Peru and Chile. A. Normal, August-September. B. Normal, February-March. C. Abnormal, 1892. After Schott.

normality, however, occurred in the late summer in certain years, notably in 1891 and 1925, and to a less degree in 1939, 1940, and 1941. These marked abnormalities are due to a widespread movement of warm water from the north, along and against the coast. Schweigger thinks that two different phenomena are involved. One is the development of a strictly coastal counter current, locally called *El Niño*, originating from the Gulf of Guayaquil and flowing southward along the Peruvian littoral. Both Vogt (1942) and Schweigger believe the true counter current is of little importance. The other phenomenon is the movement from the north and west of warm oceanic water towards the northern Peruvian coast and sometimes far southward along the coast. This latter phenomenon is usually called *El Niño* by oceanographers writing outside Peru. Schweigger indicates that it is to be regarded as a convectional movement, due to the much greater density of the cold coastal water than the warm oceanic water. If the forces producing the upwelling weaken, then the warm water moves in from the north and west as a counter current. This tends to happen annually at the height of the southern summer but is usually not well marked save in the north of Peru. Vogt (1942) found an increase in the westerly component of the wind prior to the development of the high summer temperatures of 1939 and 1941, notably between October, 1940, and February, 1941, as water temperatures rose. In the southern autumn, as late as May or June, movements of this sort have been recorded, notably in 1923 (Lavalle, 1924), 1930, 1935, and 1939–1941. Both the counter currents of oceanic origin and the true littoral *El Niño* tend to appear at the same time after Christmas and in the spectacular abnormal years doubtless cannot be distinguished. The influx of warm water in extreme cases is great enough to raise the mean annual surface temperature of the whole coast, as is seen when Schweigger's map of the isotherms for the abnormal year 1941 (fig. 4a) is compared with that for the normal year 1942 (fig. 4c).

Schott shows that in 1891 the immense development of the counter current was accompanied by a movement southward of the meteorological Equator and a consequent

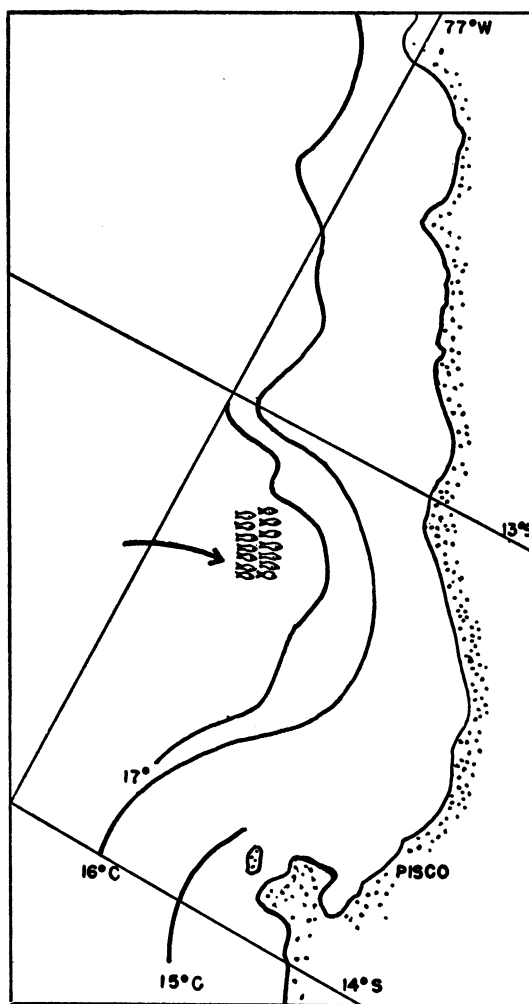


FIG. 6. Localization of fish shoals with respect to the circulation pattern off Pisco Bay. After Schweigger.

migration of the Northeast Trade Wind over the Isthmus of Panama. Water from the Gulf of Panama and from the Equatorial Counter Current moved southward, and the whole coast north of Pisco experienced coastal water temperatures in excess of 25° C. (fig. 5c). Such spectacular and catastrophic developments of what is apparently a normal condition in summer are, however, rare. They are accompanied by a marked increase in rainfall which may, as in 1925, affect the entire Peruvian coast, and the rainfall records from northern Peru¹ are more valuable in

¹ The rainfall on the central coast is less indicative, as it consists mainly of drizzle. Heavy rain may occur at

tracing past manifestations of a pronounced counter current than are the more sporadic records of water movements and oceanic temperatures. In every marked outbreak a great disturbance of the whole marine biota takes place, and this disturbance has a most serious effect on the guano birds, possibly primarily by destroying their food supply or, more probably, by making it temporarily unavailable. This matter will be considered in greater detail below.

The rainfall record, of a purely qualitative character, kept between 1791 and 1891 at Piura, 40 kilometers inland from the coast in latitude 5° S., and published by Eguigüen (1894) is discussed by Schott, who speaks of the rain as non-periodic. It is, however, commonly supposed that seasons of abnormal rainfall, high temperatures, and biological catastrophes recur every seventh year. The evidence presented for the twentieth century set out in detail in figure 17 is in favor of this hypothesis. For the second half of the nineteenth century the rainfall record gives a similar suggestion of seven-year periodicity. The hypothesis of regular recurrence, however, necessitates assuming that not only are some years, as 1891 and 1925, vastly more abnormal than others, but that some abnormal years deviate so little from normal years that they have passed unnoticed. It is, moreover, necessary to suppose the cycle has a period rather under seven years. The annual cycle and the cycle of just under seven years will usually be out of phase, but since the observed phenomena are confined to the late summer, the progress in phase difference produces a discontinuous advance in the occurrence of rainy years and six-year intervals may appear, as, for instance, before and after 1877 and 1878, both wet years, and again sometime between 1891 and the wet or abnormal years of the twentieth century (1911, 1918, 1925, 1932, and 1939). Prior to the wet year of 1864, there is no adequate evidence of periodicity, though the rains of 1814 and 1828 are two seven-year cycles apart, and several lesser rains came between

them. As will be indicated below (p. 71), there is evidence against supposing any regular periodicity during a lapse of about 50 years at some time in the more remote past, probably in the first millennium A.D. It seems likely, therefore, that if the seven-year cycle has any reality, it is a transitory phenomenon, comparable to some of the cycles of low persistence known in tree-ring records and so of somewhat uncertain value in long-range hydrological prediction.

THE PERUVIAN GUANO BIRDS

At the present time three species of birds produce virtually all the guano deposited on the Peruvian islands. Though in the past other species appear to have played at least as great a part as these three, it is convenient to consider the three modern guano birds first, as their ecology has been exhaustively described by Vogt (1942), before passing to a discussion of the other species now of little or no economic importance. The order in which the Peruvian guano birds are described is thus determined by ecological convenience rather than taxonomic position. Apart from Vogt's recent paper much valuable information has been derived from Coker (1919) and from Murphy (1925, 1936).

Phalacrocorax bougainvillei Lesson, the guanay, is at present by far the most important species. It is a cormorant of subantarctic affinities rigidly confined to the waters of the Peruvian Current. In its general behavior the guanay exhibits a very strong tendency to form aggregates. By night the resting individuals collect on islands or, during irruptive migratory movements, on capes and headlands. By day the birds fish in immense bands, the existence of which is primarily dependent on the fact that their main prey, the anchoveta, *Engraulis ringens* Jenyns, forms gigantic schools.¹ Though the limited resting areas and schooling of the food fishes are doubtless primary external conditions for the development of aggregations of guanays, it is obvious that, unless

Piura without an increase in the amount of precipitation farther south, as apparently happened in 1939. Vogt (*in litt.*) is skeptical of the use of the Piura record; it is greatly to be hoped that he will be able to work up unpublished data on this question in the near future.

¹ Dr. Robert Cushman Murphy (verbal communication) indicates that Atherinidae may also be an important food; this, however, is not apparent from Vogt's account, but Vogt (*in litt.*) thinks that changes in the composition of the food do occur.

there were a good deal of tolerance of each other's proximity by the birds and also probably some set of reactions dependent on visual stimulation by other moving birds, the typical social behavior of the species could not exist. When hunting down anchovetas, the front members of the band start feeding, while the rear members fly up forward so that the whole band tends to encircle the school of fish like the closing of a purse seine, concentrating the food into the center or on occasions driving it out to sea. No true active coöperation between the birds is known to occur. The existence of a flock of feeding birds visible in the distance has no effect in attracting a band leaving an island, nor does the successful fishing operation of one day determine the direction of flight of the next. The birds usually leave their resting places between 6 A.M. and 10:30 A.M., returning between noon and 6 P.M. Late returns, occasionally after nightfall, indicate poor or distant food supplies, early returns depending on a rich supply of food. When food is very close at hand two or more feeding trips per day may be made, and occasional nocturnal excursions near full moon have been noted. Except in the breeding season there is much wandering from island to island. The flocks spend the night on favorable islands near good fishing grounds, and if the fishing near an island becomes poor that island may be deserted.

The breeding sites are apparently rigidly determined by temperature and therefore always are in parts of the islands exposed to the wind, as Lavalley (Lavalley y Garcia, 1918) first indicated. Lavalley also considered that wind facilitated birds taking off from and alighting on their nests. The maximum ground temperature in a part of North Chincha Island colonized by birds was found by Vogt to vary throughout the breeding season from 27.5° C. to 42.5° C., the modal maximum temperature being 33.5° C. At a station on the northern side of the same island, not tenanted by guanays, the maximum varied from 30.50° to 50° C., with a mode at 42.5° C. In an intermediate station where breeding was begun but the nests later deserted, the range was from 30.50° to 44° C., with a mode at 38° C. At a given station there is a significant correlation between the

ground temperature and wind velocity. There can be no doubt that the primary factor in determining breeding sites is adequate exposure to a cooling wind. The accompanying section (fig. 7) of part of Central Chincha Island given by Lavalley shows how the nests of the guanays did not extend into the protected part of a valley, though some guano

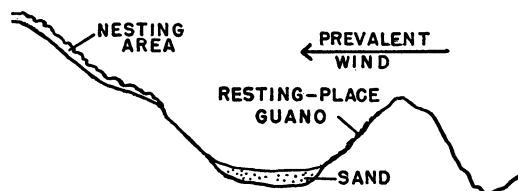


FIG. 7. Section of a part of Central Chincha Island to show the relationship of the nesting sites of *P. bougainvillei* to the prevalent wind direction. After Lavalley.

was deposited by non-breeding aggregates of birds on the lee side of the ledge that kept the wind off the deep part of the valley. When the wind is blowing from an abnormal direction for some days at the beginning of the breeding season, nesting territory may be occupied in an abnormal part of the island only to be abandoned when the wind shifts back to its normal quarter. The exposure to wind, or lack of it, explains why the flat islands of Macabí and Santa Rosa can have breeding colonies occupying 90% of their surfaces, while but 50% of the area of Blanca or Tortugas is suitable. On Lobos de Tierra only the southernmost end of the island, with adjacent islets, is windy and cool enough to support a guanay population; farther north the bird does not breed. The island of San Gallán has no guanay colony, as it has no windswept area suitable for the birds. The color of the surface is also probably involved; the black sand of Isla Vieja apparently absorbs too much heat to permit the birds to occupy an otherwise favorable locality.

The parent birds not only brood the young during the cooler hours but shade them from the heat of the sun also, and on occasions fan them with their wings. Evidence of death of young birds due to overheating was obtained by Vogt, but it is quite possible that the main deleterious effect of high temperatures is on the embryos rather than the young birds. As soon as the latter are old enough

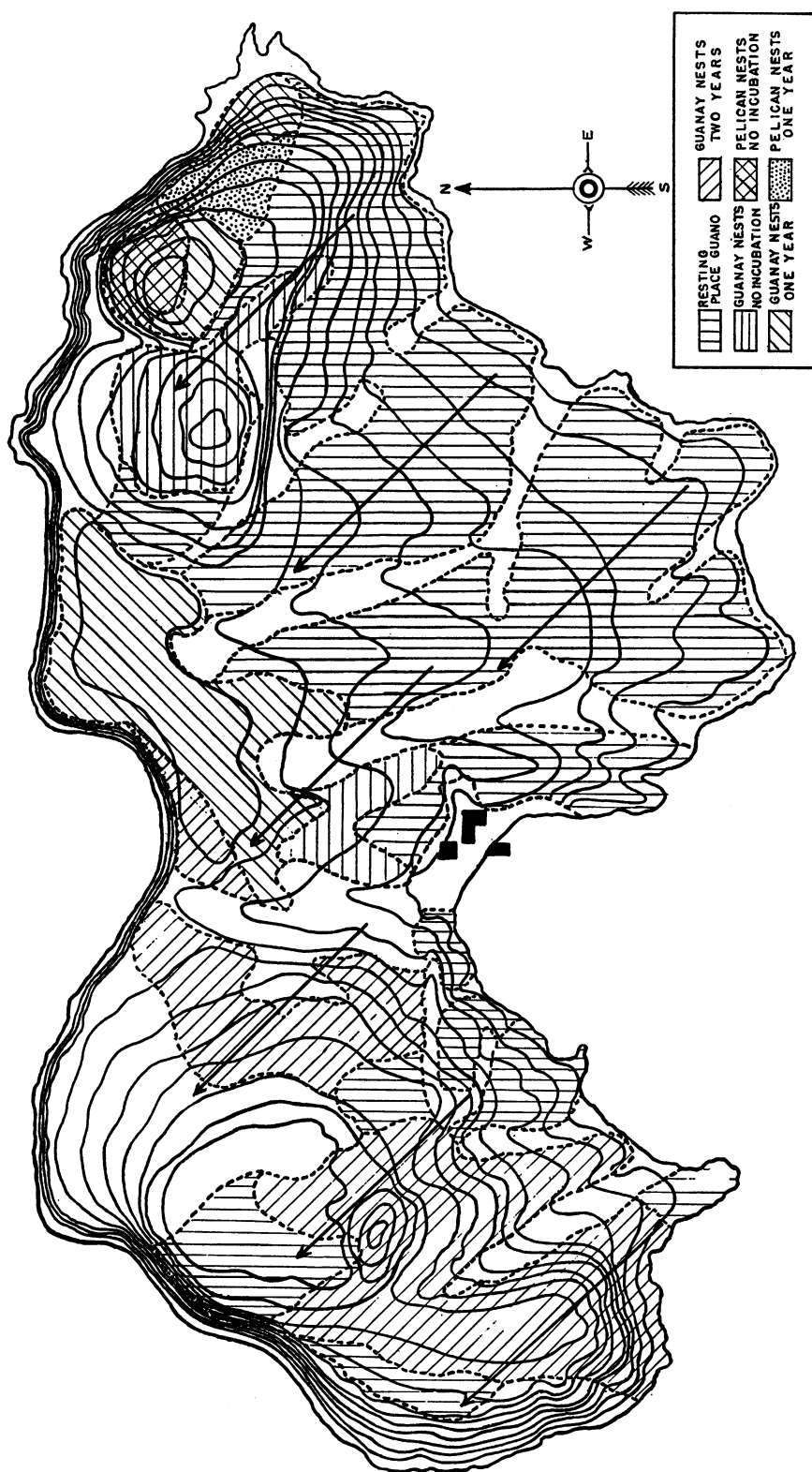


FIG. 8. The distribution of breeding birds on Central Chincha Island in 1916. After Lavalle.

(six to seven weeks) to seek the water they can reduce their temperature by entering the sea, and Vogt observed that the avidity with which this was done depended on the wind and so the cooling power of the air.

Wind is apparently not the only factor determining the distribution of nesting birds. Lavalley considered a certain slope of the ground to be favorable and also that bare rough rock was better than sandy or pebbly ground or ground with many projecting stones. Sand and pebbles tend to harbor ticks, and too many irregularities make the first passage to the sea of the young birds too difficult. The relationships are well shown in Lavalley's map, here reproduced as figure 8, based on Central Chincha in 1916. The areas in which two years' nesting of guanays had occurred are presumably the most suitable for breeding. It is probable that an old guano surface is as favorable a nesting site as any, though it may provide considerable cover for ticks.

There is evidence that nesting may occur throughout the year, but the normal breeding season is in the southern spring, beginning in October. Though the variation in day length is small in the latitudes of the Peruvian guano islands, the total light energy delivered per day is probably reduced in winter owing to cloud, and it is conceivable that such variation plays a part in regulating the periodicity. The entire breeding season lasts about four months for any pair; the first month is occupied in taking a nesting site, and by courtship; the second in egg laying and incubation; the third and fourth in rearing the young. The maximum number of reports of nesting fall in November; this probably implies that most birds are in the initial courtship phase in October and are rearing chicks in December and January. There is no evidence of social courtship. The first sexually active males choose the best territories, and the breeding colony grows peripherally, the outermost pairs being at a less advanced stage than the central and susceptible to having nesting material removed by the more favored earlier breeding birds. The establishment of a breeding colony on one island apparently draws off birds that are just entering the breeding cycle from other islands. Throughout Vogt's account the general im-

pression is, in fact, very strong that, although individual restricted nesting sites are defended as territory, the island as such has no meaning to the bird save as a center for fishing activities. Even during breeding, wholesale desertions of islands have occurred, due apparently to decline in the available food supply.

Though no synchrony in breeding is achieved by the habit of aggregation, the formation of large colonies certainly has a biological value; Vogt (*in litt.*) thinks that nesting cannot take place successfully when the colony is smaller than about 10,000 birds. Chicks at the periphery are more likely to wander away and be lost or attacked by predators than are more central chicks, whose movements are controlled by the territorial defense exercised by surrounding birds. Since the circumference will vary as the square root of the number, large colonies have relatively less of the peripheral danger zone. It is possible that the disturbance of peripheral nests by adults searching for nesting materials also is inversely dependent on population size in a similar way.

Though the nests are crowded together, the mean number being 3.139 ± 0.038 per m^2 , each is defended as territory. The female appears to be more sexually avid than the male. The male shows much greater interest during courtship in obtaining material for the construction of the nest, such as stones, feathers, seaweed, and lumps of guano. Materials of this sort are stolen from unguarded nests, and a bird frightened by man sufficiently to give up protection of its eggs will still attempt to collect nesting material. Vogt thinks that, although such material tends to contaminate the guano, it is a mistake to follow the current practice of removing all of it when the guano is collected. The undue difficulty of finding such material may be a source of disturbance to the colony and so may lead to a decrease in guano production. The completed nest is a subcylindrical structure with a concave apex and consists mainly of guano (pl. 1, fig. 2). When a thick layer of guano is already present the birds apparently dig into it. The mean clutch of eggs is 3.13 ± 0.10 . Both sexes incubate and feed the young.

The total potential opportunity for fishing is obviously reduced by half during the breed-

ing season, though when the chicks are hatched the food requirements are increased. When food is abundant this is not serious, because under such conditions outside the breeding season the birds normally use only a part of the potentially available fishing time. The rearing of the chicks, moreover, takes place during those months when there are the greatest number of reports of abundant food. Vogt points out that if nest relief does not occur before midday the fishing period of one bird will be disproportionately long and of the other disproportionately short. If the average time of relief for a group is after midday it is legitimate to conclude that fishing conditions are unsatisfactory. During 15 days of observation Vogt only once found that all the nests under examination were relieved by midday. At the same time moribund adults and chicks were found to contain seaweed and other marine plants in their crops. When conditions for feeding become abnormally poor during the breeding season, desertion of the eggs or chicks is known to occur. Considering all the available reports from the guardians of the islands, Vogt finds that over 90% of the reports of total absence of birds at an island normally frequented by them and over 90% of the cases of desertion of eggs or chicks occur at times of supposed subnormal food conditions.

Vogt found from examination of 23 stomachs of guanays returning from fishing a mean content of 143.17 ± 22.5 grams of food. Thus, taking $\pm 3\sigma$ as the limit within which 99.7% cases will fall, the normal range will be 75.67 to 210.67 grams of fish per day. Vogt thinks that 50% of the catch may be digested during fishing, so that the corrected mean catch is 214.75 and the corrected maximum 316.04 grams. The mean body weight is 2072.3 ± 53.8 grams. Since captive *Phalacrocorax auritus* are known to thrive on an intake of fish equivalent to 17% of their body weight per day, by analogy the required intake of fish for the guanay would be 352 grams. This estimate, based on captive birds fed regularly, is likely to be too high but rather suggests that the corrected maximum best represents the true intake. It is reasonably certain, from a consideration of the relationship of the phosphorus and nitrogen

contents of food and guano, that the maximum estimate made by Vogt is not too great and may be rather too small. Vogt found that the quantity of guano produced on 10 squares of area 100 m² on the Ballestas Islands, during two years, was 19,293.1 kilos. Though he says this is the total production, it appears from his calculation that it is actually the mean production per square of 100 m². Each square had a mean nesting population of 303.3 pairs. Thus 606.6 birds produce 9646.6 kilos per year, or each bird 15.9 kilos per year (Vogt gives 15.8 kilos). As the young birds, after they begin to fish for themselves but prior to their first breeding season, presumably occupy, at least for a time, the island of their birth, Vogt's estimate of production per nesting adult depends in part on the activities of the progeny of that adult in their first few months of independent life, and so is somewhat too high as an estimate of guano production by a bird of mean age in unit time. Vogt (*in litt.*) thinks that the error is small because young independent birds would not congregate preferentially on the breeding areas where the measurements were made.

The guanay under favorable circumstances suffers little from the attacks of predators. The gallinazo or turkey vulture, *Cathartes aura falklandica* (Sharpe), and the gulls, *Larus dominicanus* Lichtenstein, *L. belcheri* Vigors, and possibly *L. modestus* Tschudi, eat eggs and young when they are unguarded, but when the food supply is favorable and the guanays are undisturbed this rarely can occur. The condor, *Vultur gryphus* Linnaeus, is apparently a fairly serious predator on occasions, as for instance on Asia Island at the time of Murphy's visit, but Vogt thinks that its depredations are overrated. It is certain that maximal populations in the past existed with a full complement of predators. The sea lion, *Otaria byronia* (De Blainville), which has been greatly reduced in numbers for its skins and oil and also in part ostensibly to protect the birds, is not an important predator; individual animals may eat guanays, but the toll is very small. It is actually possible that the presence of a healthy sea-lion colony is highly beneficial in that these animals eat bonitos which compete with guanays for the anchovetas. Coker considered

that bonitos, when chasing anchovetas, often drive the fish to the surface, making them accessible to the birds. It is, however, by no means certain that an unnatural increase in bonitos, however much they assisted individual birds in the way alleged by Coker, would constitute anything but a diversion of food from the standpoint of the bird colony as a whole.

The most serious ectoparasites are apparently ticks, *Ornithodoros amblus* R. V. Chamberlin, which are controlled to some extent by lizards, *Tropidurus peruvianus* (Gray). Vogt thinks that if the sanitary habits of the guano workers were better developed, fewer coprophagous flies would exist on the islands, and the lizards would be forced to search for ticks more assiduously. A disease characterized by extreme anemia, with a red cell count about half normal and frequently a pallid appearance of the feet visible from a distance, may possibly result from excessive attacks by ticks. Pebbles or sand afford a shelter for the ticks when not feeding, and Lavalley considers that the presence of vast numbers on the sandy or pebbly parts of Central Chinchá restricted the guano birds to areas of rock surface. Mallophaga are abundant on young birds and in the throats of adults; a remarkable mutual throat-scraping ceremony taking place at nest relief is described by Vogt, who thinks that it serves to dislodge these parasites. A disease that appeared to be a form of avian cholera is recorded as occurring on the Chilean coast, and Vogt found the same condition in birds apparently flying north from this region. Lavalley (1917) regarded a form of aspergillosis as an important source of death during depressions in the guanay population, finding 30% of the birds dying in 1917 to be infected with *A. fumigatus*; but Vogt, though noting the disease, did not find it of great significance. By far the most important cause of the decline in numbers of birds and of guano produced noted during Vogt's visit from the peak year of 1939 to the lowered populations of 1941 was failure of food supply and consequent starvation.

Migration of an explosive or irruptive sort apparently occurs after the breeding season. The greater part of this movement is to the south, the results from recovery of banded

birds away from the banding stations being:

	1940 48 RE- COVERIES	1941 98 RE- COVERIES
To south:		
Chile	42%	47 %
Peru south of banding station	33	33.6
To north:		
Peru north of banding station	25	15.2
Ecuador	0	4.1

It is suggested that the dominant southern movement of these birds is due to a corresponding movement of the anchovetas. It must, however, be noted that the years in which these observations were made were both more or less abnormal (see p. 54).

Sula variegata Tschudi, the piquero, is at present the second most important bird of the region but far inferior in its output to the guanay. In many respects the ecological requirements of the two species are similar, but there are also extremely interesting differences. Though fishing for anchovetas in large flocks is the normal mode of feeding, the piquero definitely is less gregarious than the guanay. It may sometimes be encountered singly and is never found in such immense bands as is *P. bougainvillei*. Moreover, though usually nesting in large colonies, single nests isolated from the adjacent colonies may be found. In feeding, the piquero dives from a greater height than does the guanay and may well reach a greater depth. Though *Engraulis ringens* is the chief food, Coker believes *Munida* and other small Crustacea to be eaten, and Vogt thinks that the species is less dependent on the anchoveta than is the guanay. The breeding colonies of the piquero may be either on the pampas or on the cliffs of the islands. The presence of wind is apparently less necessary than in the case of the guanay. The main breeding season is coincident with that of the guanay. It is clear from Murphy's (1925, 1936) account of South Guañape that the preferred sites at the top of the gently sloping pampa were occupied by the first birds ready to breed and that the colony showed no social synchrony. The mean density of nests is given by Vogt as 1.6 per m², much less than in the case of

the guanay, each constituting the center of a small territory. Nesting material is collected, by the male particularly, but it appears to be primarily of symbolic rather than structural importance. The normal clutch appears to be two or three eggs; incubation begins with the laying of the first egg and lasts about 40 days. All chicks are reared; in this the piquero differs from the more oceanic boobies which usually rear but one chick even if two eggs are laid.

The existence of the piquero nests on the pampa and on the ledges of cliffs gives rise to an interesting problem in competitive relations and historic changes in populations.

Tschudi (1846), who described *Sula variegata*, says that the species makes nests in the sand, which implies a flat nesting site. Raimondi (1856) stated that in 1853 the species confined itself to the interiors of the islands, but later (1874) modified his statement, saying that at times they cover a part of the islands. Coker (1919) in 1906–1908 found the piquero to be strictly confined in its nesting habits to the ledges of cliffs (pl. 2, fig. 1). By 1913 Forbes noted piqueros occupying, if not breeding on, the pampa of Macabí Island. Murphy in 1919 found colonies of the kind implied by Raimondi on the pampas of several islands, notably on South Guañape Island. Murphy's photograph of this colony here reproduced (pl. 2, fig. 2) could not, according to Coker (1935), possibly have been taken in 1908.

It appears, however, from Vogt's account that at present the guanay tends to displace the piquero from flat areas except where they are too warm for the former bird. Murphy suggests that the restriction of the piqueros to the cliffs, during the early years of the present century, may have been due to competition with pelicans. The latter bird is certainly less abundant than formerly, and where it has increased locally, as on North Chincha, it can displace the piqueros. Since, however, the numbers of pelicans can hardly have made up for the deficiency of other birds indicated by the low guano returns, it is unlikely that when Coker visited Peru flat sites were entirely unavailable for the piquero because pelicans occupied them. Though Vogt thinks the pampas were originally preferred, it seems probable that when the popu-

lations were relatively small and nesting sites were determined by density independent factors, the piqueros first chose ledges on cliffs. As the populations of both guanays and piqueros increased, the piqueros spread onto the pampas, but the latter were also more and more occupied by guanays. When competition began, the conditions imposed by the cultivation of the islands as guano sources, with continual human interference, apparently permitted the guanay to force the piquero back somewhat, in a way that probably did not take place in Tschudi's and Raimondi's time, when the guanay was scarce on the islands with guano caps and the pelicans were found mainly on outlying rocks. Vogt points out that danger from predators is less great on the cliffs than on the pampas, and Murphy notes that the birds breeding on the latter are more easily frightened than are those nesting on the cliffs. The young birds wandering from their nests are, however, far more likely to be lost from the cliff sites than from the pampa, where they will continually be forced back home by adjacent birds. It is indeed apparent from the works of both Murphy and Vogt that a great number of young piqueros are lost annually by falling from the cliffs, while the loss from predators on the flat sites is small. The suggested choice of the cliff instead of unoccupied pampa at the time of Coker's visit therefore seems rather paradoxical. The synecological relations of the piquero appear similar to those of the guanay. It is, however, much more liable to be attacked by the skua, *Catharacta skua chilensis* (Bonaparte), which forces it to disgorge its catch. Tschudi concluded from the study of captive birds that 3.5 to 5 ounces, i.e., 99 to 142 grams, of wet guano, drying to 33 to 53 grams, was produced daily. His estimate corresponds to 12.1 to 19.4 kilograms per year, obviously comparable to Vogt's estimate for the guanay.

Vogt found that, after breeding, the species disperses both north and south, but the very small number of recoveries of banded birds suggests a high mortality in both 1940 and 1941.

Pelecanus occidentalis thagus Molina, the Peruvian pelican, Molina's pelican, or alcatraz (pl. 3), is a very marked subspecies of the widespread brown pelican of the tropical

and subtropical New World. It is apparently confined as a breeding bird to the region of the Peru Coastal Current, being replaced on the Ecuadorean coast by the much smaller *P. o. murphyi* Wetmore. Specimens of *P. o. thagus* have been recorded, presumably as stragglers, as far south as Tierra del Fuego (Wetmore, 1945). In spite of its association with cool waters, the Peruvian pelican appears to be far more tolerant of heat on land than is the guanay, or possibly even the piquero. It is still less gregarious than the last-named species, fishing in small flocks or alone, and goes farther out to sea than do the other birds. It is also apparently able to fish at night more successfully than the two other species. It is, moreover, definitely less dependent on the anchoveta than the guanay or even the piquero. Coker found a mullet (*Mugil cephalus* Linnaeus) over a foot in length regurgitated at a nest. The pelican is much the most easily disturbed of the important three species of guano birds, though Vogt states that a colony can reform quite soon after guano has been stripped from a breeding site. Though less prone to form large aggregations when fishing than are the other species, there are indications in the accounts summarized by Murphy (1936, cf. Vogt, 1942) that some degree of social courtship occurs among the birds of the small breeding groups into which the colony tends to be divided. Coker implies that the Peruvian pelican is more prone to attacks by ectoparasites than are the other guano birds. At the present time the pelican is a significant producer of guano on the two Lobos Islands, and small numbers nest on Santa, Isla Blanca del Norte, Don Martin, the Pachacamac Islands, and sometimes on the Pescadores Islands (Anon., 1945b). A small colony persists on outlying islets of the Chincha group, where at the beginning of the century it was a very important guano bird (Forbes, 1915a, 1915b; Murphy, 1925, 1936). It breeds or has bred as far south as the middle Chilean coast. After breeding there is some movement both north and south, reaching to both Ecuador and Chile; as has been indicated above, *P. o. thagus* has occurred as far south as Tierra del Fuego. According to Cookson (1874b) Hindle estimated that 2,500,000 pelicans, probably on one of the Lobos

Islands, produced 10,000 tons of guano annually. The number appears to refer to young birds in the nests, and would correspond to about a million pairs of adults. Thus each bird present at the beginning of the breeding season is apparently responsible for about 5 kilograms per year. This estimate may reasonably be regarded as too small.

At the present time two other species appear to make minor contributions to the guano deposits. *Sula nebouxi* Milne Edwards, of which the breeding range extends from the Lobos Islands north to the Gulf of California, is believed to be of some significance on Lobos de Tierra. Murphy (1936) states that although "not a colonial bird, strictly speaking . . . in many of the flat detritus-filled valleys of Lobos de Tierra its nests are now so thickly distributed that the total increment of guano is very large." Coker indicates that he was of the same opinion, though it appears that *S. nebouxi* scatters its guano more than does *S. variegata*.

The other bird of subsidiary importance is the Inca tern, *Larosterna inca* (Lesson). As is indicated in the section on changes in the avifauna, the Inca tern was probably a fairly important guano producer on the Chincha Islands in 1853. Murphy (1936) notes the species from Salaverry, the Guañape Islands, Palominos Rocks, Mazorca Island, the Pescadores Islands, Ancon, Callao, San Lorenzo Island, Fronton Island, Asia Island, the Chincha Islands, San Gallán Island, Santa Rosa, Vieja, and other islands in Independencia Bay and at Mollendo. It has been alleged to breed at Macabí Island and at Hormigas de Afuera and as far south as Coquimbo. It will be apparent from the list of islands given that, although the bird belongs to a monotypic genus endemic to the region of the Peru Current, it can breed on islands unsuitable for the guanay. The bird can nest in niches or hollows in rocks, or in burrows of other birds, or in excavations that it makes itself. The degree of concealment is supposed by Murphy to depend on the presence or absence of turkey vultures; Murphy states that on occasion guanays can displace Inca terns from their breeding grounds. The same author thinks that at Asia Island and the Pescadores this species makes a significant contribution.

TABLE 1

	First Year of Collection	Total Yield to End of 1944 (Metric Tons)	Yield (Metric Tons)			
			1937- 1938	1938	1939	1940
Islote Perico and Bayovar	1937-48	316	130	—	51	40
Lobos de Tierra	1924-45	53,623	504	—	9,796	4,409
Lobos de Afuera	1936-37	7,475	—	—	—	—
Macabí group	1916-17	200,824	10,166	9,617	5,898	6,187
Guañape group	1916-17	408,384	44,183	—	43,707	12,398
Santa group	1922-23	111,134	5,116	14,593	3,054	13,461
Blanca de Norte I.	1929-30	22,986	—	—	—	4,848
Tortugas I.	1934-35	43,794	14,001	—	14,194	—
Punta Bermejo y Patillo	1922-23	1,053	—	—	—	—
I. Don Martin	1922-23	237,115	—	27,911	10,133	—
Huaura group	1916-17	135,975	—	13,264	—	8,814
Punta Chancay Grita Lobos	1922-23	19,942	4,824	—	1,653	—
Tartacay	1927-28	3,165	—	338	—	—
Pescadores group	1916-17	239,254	—	19,530	—	15,616
Hormigas de Afuera group	1919-20	3,656	—	—	—	—
Northern islands and points	1933-34	6,525	—	—	—	—
Palominos I.	1909-10	7,962	—	—	—	—
Cavinzas, La Cocina, San Lorenzo, La Cruz I., etc.	1909-10	101,914	3,997	5,644	13,450	6,130
El Fronton I.	1909-10	78	—	—	—	—
Morro Solar, Huanillos, and La Chira	1909-10	831	—	—	—	—
Pachacamac group	1910-11	147,424	13,874	—	10,223	—
Punta de Chilca	1909-10	246	—	—	—	—
Asia group	1909-10	192,514	—	23,833	—	15,237
Islands and points near Cerro Azul	1909-10	7,721	—	—	—	—
N. Chincha I.	1911-12	292,212	—	31,082	—	19,466
C. Chincha I.	1910-11	166,093	—	14,002	—	6,023
S. Chincha I.	1909-10	165,971	—	8,752	—	4,346
Blanca and Ovillos	1910-11	9,695	—	—	—	—
Ballestas group	1916-17	208,338	16,344	—	16,692	—
Tres Marias islets	1910-11	98	—	—	—	—
Zarate islets	1910-11	70	—	—	—	—
Isla Vieja (Independencia Bay)	1911-13	5,248	—	—	1,730	—
Santa Rosa group	1912-13	363,459	33,792	—	19,058	—
P. Lomas	1933-34	11,476	3,015	—	—	5,832
P. Olleros and Lomitas	1912-13	530	—	—	—	—
P. San Nicolas and San Fernando	1910-11	4,971	—	—	—	—
Sombrecillos group	1910-11	10,129	—	—	—	—
Chala Atico, Ocona, and Islay	1911-12	20,941	117	—	352	80
Southern islands and points	1933-34	376	—	—	—	—
Iñani, Jesús, and Cocotea	1913-14	24,980	—	—	1,336	—
P. de Coles	1915-16	1,746	—	—	333	—
Morro de Sama	1914-15	10,807	2,273	—	506	2,727
Quilca islets and headlands	1931-32	262	—	—	—	—
Naval base	1936-37	114	—	25	—	—
Miscellaneous	1930-31	1,726	196	37	30	29

In addition to these two species two others are supposed to have been preëminent guano birds in the past. These two birds, the Peruvian penguin, *Spheniscus humboldti* Meyer, and the diving petrel or potoyunco, *Pelecanoides garnotii* (Lesson), are both burrowing species.

Spheniscus humboldti is recorded breeding from Lobos de Tierra southward to latitude 33° 20' S. It is apparently liable to breed throughout the year and generally nests in caves and burrows; it now has difficulty in finding suitable breeding sites on the guano islands. At the Chincha Islands Murphy found pairs breeding in holes dug in the sand at the base of a cliff and subject to danger of occasional flooding by the tide. This seems to be typical of the difficulties that the islands now present to the species. The small size of the most notable flock observed in recent times, one of 200 birds at Vieja Island and recorded by Murphy, indicates the generally restricted nature of the populations, in great contrast to Raimondi's account of this species as an abundant and important component of the avifauna of undisturbed islands such as South Chincha in 1853. The main cause of the reduction in the numbers of penguins is undoubtedly the removal of the thick deposits of guano in which the birds could burrow. The persecution of the species by guano workers and fisherman who used its flesh for food and its skin for making caps also must have reduced the numbers of so helpless a bird.

Pelecanoides garnotii has a similar history. Instead of being the most important bird on the guano island, it now is largely confined to the higher islands, San Lorenzo, Fronton, San Gallán, and Vieja, that do not produce guano. It is known to have nested abundantly at Lobos de Tierra, Macabí, Guañape, Pescadores, and Ballestas as well as the Chincha Islands. Yet in 1913 Beck found but a single pair nesting at Pescadores Island. The problems raised by this species are considered in a later section (pp. 61-63).

Before changes in the avian population of the Peruvian coast are considered, it is desirable to point out that Schweigger's maps of distribution of feeding guano birds suggest that certain parts of the coast are more densely populated than are other parts. In particular a stretch of coast between Huar-

mey and Chimote is rather deficient in records, and the whole southern part of the Peruvian coast, notably between Aricá and Punta Islay and about Infiernillos, seems to have fewer birds than does the central region. Though variation in the insularity of the coast is certainly an important factor in determining this deficiency, it is possible that the distribution of fish shoals is also in part responsible for the uneven distribution of birds and that the concentration of fish depends on the position of the anticyclonic swirls. The observed correlation is apparent in figure 9.

THE POSITION, NATURE, AND IMPORTANCE OF THE VARIOUS PERUVIAN ISLANDS

The various islands and mainland localities which now yield Peruvian guano are given, on the authority of the Compañía Administradora del Guano, in a series of maps published by Murphy (1936) and here reproduced (fig. 10).

These maps indicate at least 147 islands and 21 mainland localities now producing guano. The relative importance of these localities can be judged by the total quantities collected since the rational control of the bird islands was instituted, and by the figures for some of the recent collecting campaigns which indicate the maximum modern yields in 1937-1939, as well as the lower yields in 1940 due to the catastrophic reduction in production that began in 1939 and continued until 1942 (table 1).

It will be apparent that certain localities are of preëminent importance. The Macabí and Guañape groups, Don Martín, the Pescadores and Asia groups, each of the three Chincha Islands, and the Santa Rosa group have each produced during the period of supervision by the Compañía Administradora over 162,700 tons of nitrogenous guano, or over 5% of the total yield of the coast. Under favorable circumstances over 10,000 tons can be expected to be produced on most of these islands or groups every second year. The Santa, Huaura, and Pachacamac groups are almost as productive. When these modern records of current guano production are compared with the figures for the accumulated guano removed in the last century it is apparent that while all the islands that yielded

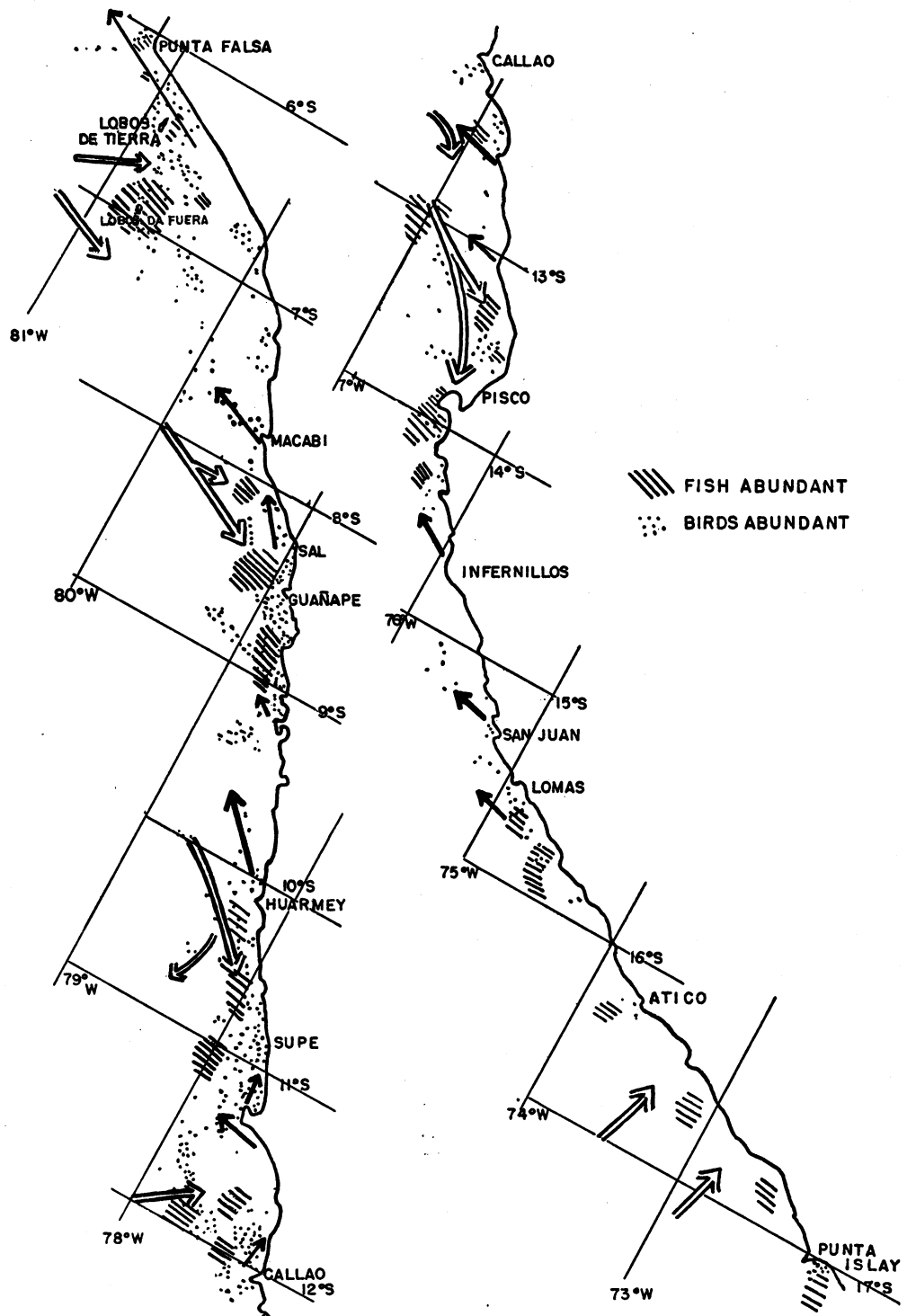


FIG. 9. The distribution of the principal loci of accumulation of fish and birds off the Peruvian coast. After Schwiegger.

large quantities of old nitrogenous guano are now highly productive, not all the good modern islands had guano caps. The persistence of guano on an island as a significant biogeochemical deposit clearly involves factors other than those regulating production, but it is necessary to examine the more important individual islands before any general conclusions relating to this matter can be drawn. In the following pages the available information on the history and present state of the significant islands is presented.

THE NORTHERN LIMIT OF THE GUANO COAST

There have been claims made that guano "very little inferior to that of the islands of Peru" has been found on La Plata Island (latitude $1^{\circ} 18' S.$, longitude $81^{\circ} 04' W.$) and on other islands in the vicinity (Great Britain, Parliamentary Sessional Papers, 1854-1855, Letter No. 2, Consul [Walter] Cope to the Earl of Clarendon). These records are presumably quite unreliable; if any guano occurs on this part of the coast it is most unlikely to be nitrogenous or "very little inferior" to that of the islands of Peru.

PELADO

LATITUDE $1^{\circ} 57' S.$, LONGITUDE $80^{\circ} 38' W.$

This may be included among islands in the vicinity of La Plata. It is much more barren than the latter or than the adjacent coast, has colonies of *Pelecanus o. murphyi*, *Fregata magnificens rothschildi*, and *Sula nebouxi* and has yielded one shipload of guano (Murphy, 1936). The most northern Peruvian guano island is evidently Islote Perico, just off Bayovar (latitude $5^{\circ} 50' S.$, longitude $81^{\circ} 06' W.$)

LOBOS DE TIERRA

LATITUDE $6^{\circ} 26' S.$, LONGITUDE $80^{\circ} 05' W.$

The most northern of the important Peruvian guano islands is elongate, about 9 kilometers long in a north-south direction, and with a maximum breadth of about 3.2 kilometers. Raimondi (1897) indicates the island to be composed of crystalline rocks, mainly granite. The interior is occupied by a range of small hills, most of which are not over 60 meters high, though at the south end the highest hill reaches 91 meters. Between these hills there are broad gulleys, the floors of

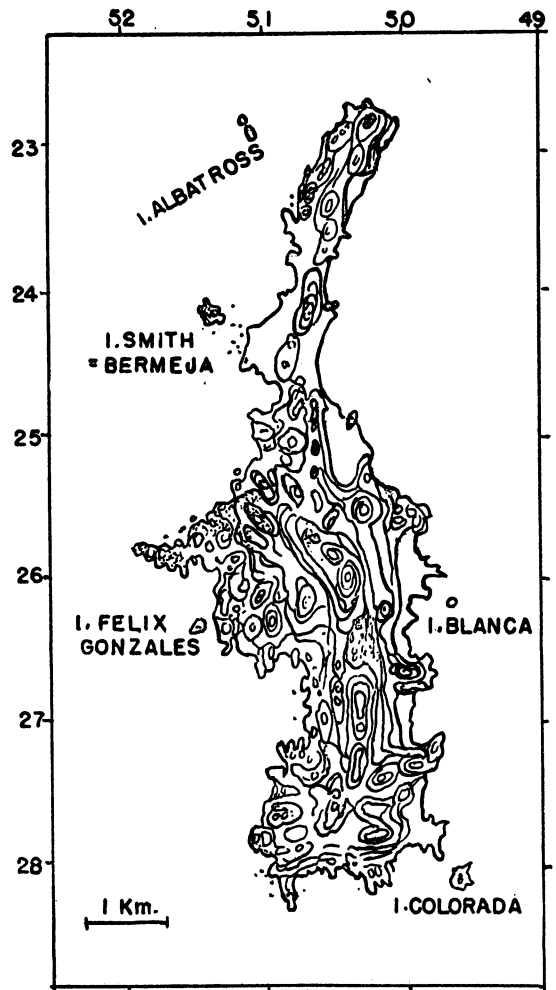


FIG. 11. Map of the Lobos de Tierra group.

which are apparently little above sea level. Three small islets lie off the main island, Bermeja and Felix Gonzales off the western coast and Colorada off the southern end (fig. 11).

The guano deposits on Lobos de Tierra were not continuous but lay on the bottom of the valleys, on the small islets, and on certain salient promontories, notably Punta Corcovada in the middle of the west coast, Punta Colorada, and a small promontory opposite the islet of Felix Gonzales (Carter *in* Rivero, 1852). White guano occurred on Punta Corcovada, forming a deposit about 1.7 meters thick at the time of Carter's visit. The form of this promontory is said to have favored accumulation, as the guanera was protected

from the winds. The other guano is described as red or dark gray, the latter perhaps containing seal feces. The three islets appear to have had regular guano caps, like those on the Chincha Islands, covering most of their surfaces.

Isla Bermeja, an islet 419 meters long, 186 meters wide, and 25 to 30 meters high, about 250 meters from the main island and connected with it by a drying reef, had a deposit of superior guano of area 38,000 m², maxi-

dominantly red, interstratified with layers of gray- and ash-colored guano, and to have had a very strong smell of ammonia. The island had an immense concourse of birds, nesting both on the surface and in burrows.

Carter estimated the total amount of guano present on Lobos de Tierra and the associated islets as 477,850 toneladas, the Bermeja deposit being the most extensive of all the guaneras of the group. A later survey made in 1863 resulted in a much higher esti-

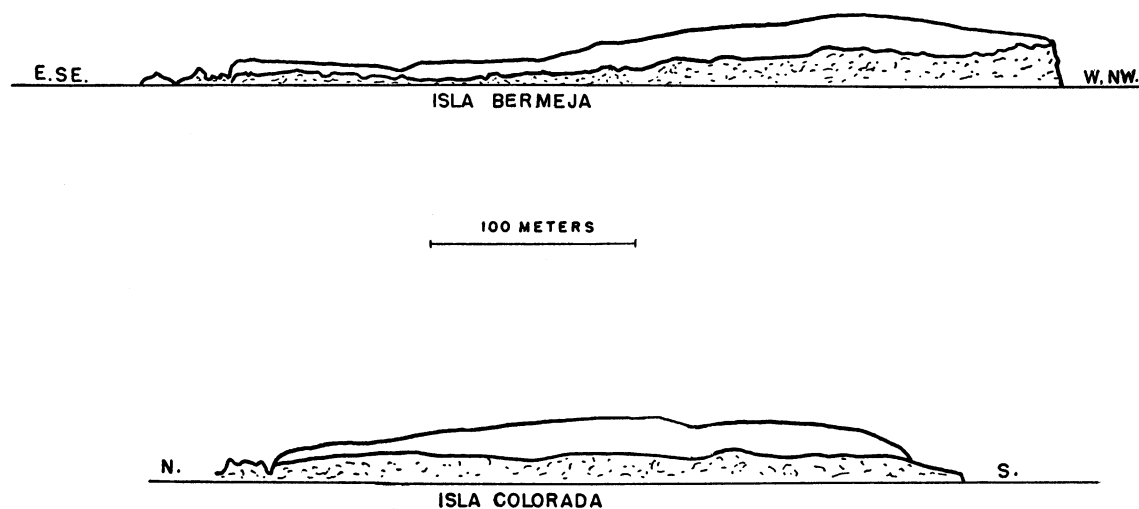


FIG. 12. Sections of Isla Bermeja and Isla Colorada, Lobos de Tierra group, to show virgin guano caps. After Carter *in* Rivero.

mum thickness 11 meters and mean thickness 5.8 meters. The deposit is said to have been covered with a layer of *salitre*.¹

Felix Gonzales, a small islet 76 meters long, 59 meters wide, and 12.7 meters high, also on the western coast of the main island, had a cap of superior guano of area 4760 m² and mean depth 3.4 meters. No indication of the nature of the surface layer was given by Carter.

Isla Colorada, an islet at the south end of the island, about 280 meters long, 150 meters wide, and 21 to 25 meters high, had a guano cap of area 22,900 m², maximum depth 11.9 meters and mean depth 6.4 meters (fig. 12). The material was stated to have been pre-

mate, namely, 7,347,736 toneladas, which certainly was excessive. Duffield (1881) considered that at least 800,000 tons of good quality material was present in 1877. By good quality, Duffield appears to mean that the guano contained more than 2% nitrogen. At the time of his visit some 40 ships were waiting to load. Between 1893 and 1910, 259,000 tons of guano were removed by the Peruvian corporation; this material usually contained 2% N and 16% to 20% P₂O₅, though occasional cargoes containing up to 12% N were exported. A survey made in 1910 supposedly indicated 959,314 tons of more or less phosphatic guano to be present. Between 1910 and 1933, 116,000 tons were removed, so that 843,000 tons might have been expected in the latter year. Actually de la Puente (1933), from whose paper all these data are taken, estimated only 147,861 tons, contain-

¹ The English version gives nitrate of soda, following the usual translation, but in default of definite analytical evidence the presence of large quantities of nitrate should not be unreservedly accepted.

ing 1.12% N and 15.19% P_2O_5 . The reserve in 1893 must therefore have been rather over half a million tons. In view of Duffield's statements and in the light of these figures an initial reserve of the order of 1,000,000 tons containing at least 16% P_2O_5 seems a reasonable, conservative estimate. This would correspond to a phosphorus accumulation of 70,000 tons P. According to the Compañía Administradora del Guano, fresh guano at Lobos de Tierra usually contains 11% to 13% N, of which material up to 3000 tons may be produced in a two-year period (Anon., 1945b). Some of the old guano apparently contained at least 13% N (Anon., 1872), but the detailed analysis given below refers to a much more decomposed material.

Murphy states that the summits of the hills are covered with a dazzling coat of guano glass, presumably a calcium phosphate. Duffield found good, though opaque, crystals of salammoniack at this locality.

The first observations on the ornithology of Lobos de Tierra are by Delano (1817) who records "vast numbers of different kinds of oceanick birds," including one that he had not seen before, which may be certainly identified as *Rynchops nigra*. Murphy suggests that his observation that this bird is "an excellent eating bird" indicates the cause of its present rarity on the Peruvian coast. He further writes that the larger birds of the island "form rookeries, which to view with a spy glass at a distance had a pleasing appearance, and give rise to a comparison that was made use of by our people ever after, viz. Bonaparte's and Suwarrow's armies." The subsequent account indicates that Bonaparte was in command of the boobies and Suvárov of the pelicans.

According to Coker (1919) there was a good guanay colony, apparently on the islet of Bermeja, during his investigations in 1907-1908. Pelicans were evidently common, and *Sula nebouxi* was abundant. Forbes (1914a) states that the breeding area of pelicans and guanays consisted of the promontories of Canevaro and Vivero on the west coast, the islands of Albatross and Smith (= Bermeja of Carter) on the west coast, as far as the island of Larrañaga (? = Colorada of Carter), on the east coast, and the northern part of the island up to the

last rocks. Much of the new guano being formed was produced by *Sula nebouxi*. The catastrophic death of the pelicans noted by Forbes is discussed below (p. 52).

Murphy (1936) records *Sula nebouxi* as the dominant bird at Lobos de Tierra and states that there were, in 1919, eight pelican colonies, none of which contained more than 200 nests. His figure (1925, fig. opposite p. 336) of the coast of the island indicates many guanays. Vogt, as has been previously indicated, says that the last-named bird is now confined to the extreme south of the island, and the adjacent islets.

It is a matter of some interest that the small islets seem particularly favored by the guanay, doubtless, as Vogt supposes, on account of the cool air passing over them. These small islets had well-developed guano caps, which were presumably largely produced by guanays.

LOBOS DE AFUERA

LATITUDE 6° 58' S., LONGITUDE 80° 42' W.

A group of two very irregular islands and various small islets, situated about 54 kilometers from the coast, and apparently composed of metamorphic rocks (quartzites, Raimondi, 1897; schists, Murphy, 1925). The northern island is about 4.3 kilometers long, the southern about 5.5 kilometers long. As far as can be ascertained the surface of the islands is similar to that of Lobos de Tierra, very numerous small hills rising to altitudes not exceeding 60 meters. The guano evidently formed distinct deposits in the valleys between the hills; Duffield (1881) indicates that eight such guaneras were known. Raimondi states that the survey of 1863 disclosed a reserve of 607,086 tons of guano, though Duffield believed that an aggregate of 1,000,000 tons, of which 650,000 tons were of good quality containing more than 2% ammonia, was present. Between 1896 and 1912 200,000 tons containing from 2% to 4% N and from 18% to 21% P_2O_5 were removed. A survey in 1910 disclosed 104,416 tons (de la Puente, 1933) containing 1.65% to 10.63% N and 13.78% to 26.18% P_2O_5 . From the time of the survey until 1925, 69,820 tons were removed. In 1933 no old guano of value was found by de la Puente. The original de-

posit must have been at least 600,000 tons, containing 20% P_2O_5 , i.e., 52,400 tons P.

Murphy (1925) states that in 1919 the lower regions of the islands were covered with a dust of decomposed rock and that powdery guano filled the valleys to a depth of at least 6 feet. As on Lobos de Tierra, the summits of the hills were coated with a guano glass compared with that on St. Paul's Rocks or on Barrington Island in the Galápagos.

Coker noted about a hundred thousand pelicans occupying a rookery of many acres on the northern point of the main eastern island and on an associated islet. In 1908 this rookery was disturbed by guano diggers, and in that year six or more small colonies containing in all about 2000 nests were observed on the eastern island. Most birds had migrated to the western island where between 10,000 and 20,000 nests were present. Some birds had moved to Lobos de Tierra. By 1919, however, Murphy noted about 200,000 pelicans, though he says the bird population was much reduced from its size at the time of Coker's visit. Murphy also noted that the booby population consisted of about equal numbers of *S. nebouxi* and *S. variegata*, but he observed no guanays.

MACABÍ ISLANDS

LATITUDE $7^{\circ} 49' S.$, LONGITUDE $79^{\circ} 28' W.$

A pair of islands joined by a suspension bridge. The northern island, though smaller, is higher than the southern, reaching a height of about 30 meters, though there is evidently little difference in the altitudes of the two islands. Forbes says the southern island is about 160 meters long and 100 meters wide. The Macabí Islands are said to have suffered much cutting by the sea and to have deep caves (Anon., 1945b). Forbes (1914a) comments on their suitability for birds on this account, and Vogt says that 90% of the surface of the islands can be occupied by guanays.

In view of the very large numbers of archaeological finds that have been made on the island, it is most unfortunate that virtually no details relating to the deposit exist. The most important authority is Hutchinson (1873) who gives a sketch of the islands, here reproduced (pl. 4, fig. 1). Hutchinson quotes

a letter, dated September, 1871, by Mr. F. Heaton, then British Vice-Consul for the Guañape and Macabí Islands. He says that the rock of the islands is only 30 meters high, while the height to the top of the guano was 72 meters. Hutchinson's figure indicates that the chief deposit was on the larger island, while the residence of the working officials was on the smaller island. A third still smaller islet or rock lies apparently south of the larger island. The whole of the mass of the larger island above the level of the suspension bridge is evidently guano.

Raimondi (1897) says that samples of Macabí guano collected in 1867 contained 6.58% N and 14.95% P_2O_5 , but that as exploitation continued, better material containing more nitrogen was found below the surface. This observation indicates that the surface layer differed from the deeper part of the deposit.

The total quantity of guano present in 1863 on the Macabí Islands was estimated as 681,047 toneladas (Raimondi, 1897), though Cookson (1874b) gives a value of about 575,000 tons, which he believes to have been an underestimate. Stanley (1874) states that 400,000 tons were estimated as present in 1871, but that at the time of writing (January 16, 1874) more than that amount had already been exported. The original reserve clearly must have been of the order of the 627,000 metric tons implied by the 1863 survey. If this contained 12% P_2O_5 , the original deposit was equivalent to 32,800 tons P.

Forbes says that when he visited the Macabí Islands in 1913 the interior plains were covered with breeding *Phalacrocorax bougainvillei* and with *Sula variegata*, while the scarps were populated by *S. variegata* and *S. nebouxi*. At the present time the islands are known to have a large breeding population of guanays (Vogt, 1943; Anon., 1945b).

GUAÑAPE ISLANDS

LATITUDE $8^{\circ} 34' S.$, LONGITUDE $78^{\circ} 56' W.$

A group of islands, of which the most important are the South Island and the North Island; a group of central islets lies between them, and to the north are the outlying rocks of Los Leones and Cantores. The South Island, which is 690 meters long, 570 meters

wide (Hutchinson) and 165 meters high (Raimondi; Forbes gives 500 feet), is the most elevated member of the group. The North Island, which is 1050 meters long and 700 meters wide, has a greater area than the others and is surrounded by a narrow terrace on which the buildings of the guano administration now stand. The terrace is well shown in the photograph given by Murphy (1936) and here reproduced (pl. 4, fig. 2) and in that given by Johnson and Platt (1930). Within the terrace a steep, cliff-like slope rises to a flat interior pampa.

According to Raimondi (1897), prior to exploitation in 1869 the reserve of guano was 1,568,550 toneladas, or 1,443,000 metric tons. Middendorf gives a round figure of 1,500,000 tons. Hutchinson states on the authority of Heaton that 838,853 tons were removed from the North Island between the beginning of work in 1869 and September 30, 1871, and at that time 12,000 to 15,000 tons remained on the island, as well as an estimated 450,000 tons on the South Island. On this basis the total reserve would originally have been about 1,300,000 tons which, with a P_2O_5 content of 12.75%, is equivalent to 72,200 tons P. Hutchinson states that Heaton informed him that the height of the top of the guano on the South Island was 160 meters and the height of the base of the guano in the working in September, 1871, was 120 meters. This does not necessarily imply a thickness of 40 meters. The richer deposit on the flatter North Island, however, may have been thicker. As on Macabí, the surface guano was poorer in nitrogen than the deeper material, Raimondi recording but 4% to 5% N in the superficial layers. Forbes says that at the time of his visit the South Island was covered with compact piles of stones that caused a reduction in the available breeding spaces. These may have been the remains of a conglomerate below the old guano.

The islands were rich in archaeological material; the available data have been re-evaluated by Kubler whose conclusions are published elsewhere (Kubler, 1948). It is worth noting that a stratum said to have been 5 feet thick and extending over 1000 feet contained numerous fragments of textiles (Harris, 1870). There were but 3 or 4 feet of guano over this stratum, which must have

been formed fairly recently. The occurrence is of interest as indicating continued deposit during a period when the island was habitually visited by the pre-Columbian inhabitants. Other archaeological material occurred at depths up to 8.2 meters on the South Island and 12.2 meters on the North Island.

Hutchinson figures a mummified penguin, found under 10 meters of guano and associated with a textile fragment. Mummified guanays from a cargo of Guañape guano received at Charleston in 1870 are described below (pp. 64, 65).

Forbes noted the sides of the cliffs of the South Island tenanted by *S. variegata*, while guanays occupied the plains. Some pelicans occurred around the South Island and on the summit of the North Island. Both *Phalacrocorax gaimardi* and *P. o. olivaceus* also occurred, as well as *Larosterna inca*. He also noted a few *S. nebouxii* breeding at Guañape. Murphy found both *Sula variegata* and *P. bougainvillei* inhabiting the North Island, but the latter species did not occur in 1919–1920 on the South Island, which was almost entirely tenanted by *S. variegata* save for *P. gaimardi* and *L. inca*, which occupied a narrow zone along the shore. *Sula nebouxii* seemed to have disappeared as a breeding species. The modern yield of the island may reach 40,000 tons in a two-year period, the guano containing 13% to 16% N.

The old guano of Guañape was remarkable for its contents of discrete crystalline minerals, which are discussed at greater length below (pp. 91–94).

CHAO ISLANDS

LATITUDE 8° 56' S., LONGITUDE 78° 47' W.

A pair of islands south of Guañape, of which the southern has a mean diameter of about one-half a kilometer and rises to an altitude of about 38 meters (United States Hydrographic Office, 1916a). The islands are said by Raimondi (1897) to have had a light coat of guano. Fallon states that 2000 tons were estimated to have been present, and that actually 1273 tons were obtained. In 1877 a reserve of 800 tons was present (Duffield). Forbes (1914a) records *Phalacrocorax gaimardi*, *Sula variegata*, and a few pelicans.

ISLANDS BETWEEN CHAO AND THE BAY OF FERROL

Eight islands or groups are indicated on the map of the Compañía Administradora, between latitudes 8° 55' S. and 9° 10' S. Of these, the islands La Viuda, Corcovado, Santita, Santa, and Mesia appear to form the Santa group of the table of modern guano production, while the entry for Isla Blanca del Norte in the same table may include material from the adjacent Ferrol Islands, El Colorada, and other islands to the south. None of these islands is now of great importance, and none save Isla Blanca is mentioned by Raimondi as bearing even a thin deposit. Santa Island, about 3.2 kilometers wide and 67 meters high (Forbes, 1914a) is of peculiar interest because Carter (*in* Rivero, 1852) was told that 15 or 20 years prior to his visit in 1847 the island had been perfectly bare, without a bird colony, but that subsequently birds had settled on the island which in 1847 was beginning to acquire a deposit. At the present time both guanays and pelicans are recorded as occupying Santa and Isla Blanca del Norte (Anon., 1945b).

In spite of the relative unimportance of most of these islands, it would seem that the small and low islet of Corcovado had enough ancient material on it for Corcovado guano to be designated as such when it appeared in the English market (Aikman, 1894). Fallon says that 11,585 tons were estimated to have been initially present on the island, but that 11,847 tons were actually removed. Duffield (1881) indicates the following reserves at the time of his visit in 1877:

	TONS
Corcovado	3,000
Santa	100
Bay of Ferrol	22,000

It is clear that much guano had been removed from Corcovado before Duffield's estimate was made.

Carter found no guano on Ferrol Island, but says there was a triangular patch on the mainland opposite, occupying an area of 61,400 square varas. This was mostly seal dung, but there was bird guano on either side of the seal deposit. Forbes says numerous guanays occupied South Ferrol Island and that pelicans and other birds occurred in the bays.

Slightly farther south El Dorado Island (latitude 9° 12' S., longitude 78° 36' W.) and "Small Island Pajarros" (latitude 9° 12' S., longitude 78° 26' W.) are mentioned by Duffield as bearing 6000 tons and 250 tons, respectively; while patches on Pajaros Island are mentioned by the "South America pilot," as they are on Lobos Island, which is marked as yielding guano on the Compañía Administradora's map in this region.

ISLANDS BETWEEN LATITUDES 9° 20' S. AND 10° 30' S.

The map of the Compañía Administradora marks but seven islets and two headlands as yielding guano, and no specific figures for modern production are available. Duffield gives the reserves in 1877 as follows:

	LATI- TUDE	LONGI- TUDE	TONS
Tortuga	9°21½'S.	78°27'W.	700
Mongon	9°40'S.	78°25'W.	23,000
Mongon 2d	9°40'S.	78°20'W.	30,000
Mongoncillo	9°45½'S.	78°17'W.	6,000
Cornejos	9°53'S.	78°15'W.	500
Erizos	9°55'S.	78°14'W.	5,000
Huarmey	10°00'S.	78°12'W.	500
Huarmey	10°02'S.	78°11'W.	3,000
Bay of Gramandal	10°25'S.	78°00½'W.	10,000

None of these localities can have had significant old deposits, and none is mentioned by Raimondi as bearing guano, though Fallon records that the Bay of Gramandal was estimated to have had 7000 tons.

DON MARTIN

LATITUDE 11° 03' S., LONGITUDE 77° 40' W.

A small islet, said to be about 20 meters high (United States Hydrographic Office, 1916a), which is now evidently a very important source of guano. Like Santa Island, the island has apparently acquired a bird colony in relatively recent times. In 1821 it was the site of a military hospital and at that time had neither birds nor guano, though by the time of Carter's visit in 1847 a bird colony was established and guano was beginning to accumulate. Raimondi indicates that the island was of even height and whitish in color. According to de la Puente (1933) the high modern yield of Don Martin is due to

its surface having been cleaned and so rendered suitable for a bird colony. However, Vogt (*in litt.*) found no evidence that cleaning islands makes them more favorable for birds. Forbes (1914a) visited the island after the guano had been collected and found it deserted. It is stated now to have a dense breeding population of guanays, a smaller number of piqueros, and few pelicans (Anon., 1945b).

HUAURA ISLANDS

LATITUDES 11° 22'–11° 26' S., LONGITUDES 77° 23'–77° 27' W.

Only one of about 10 islands, namely, Mazorca, or Mallorca, is mentioned by Raimondi as having a deposit, which he says was ocher yellow. Heiden says that there was a notable quantity of guano on the island, but Carter (*in* Rivero, 1852) found on Marzoque, presumably the same locality, no considerable deposit, though he says many piqueros were caught there. Forbes says the island is 1389 meters long and 617 meters wide and 122 meters high. The south slope was covered with nesting guanays when Forbes visited the island in 1912; *S. variegata* occupied the cliffs, but no pelicans were observed. Forbes also notes large stones lying over the surface of the island.

EL PELADO

This, the southwesternmost member of the Huaura group, is mentioned by Carter (*in* Rivero, 1852) as a gigantic table about 170 meters (200 varas) high, of a white color. The island was said to contain little guano but to be a great resort of birds, to which the Indians came to fill their canoes with piqueros, huanaes, and eggs. Twenty-four thousand birds and 12,000 eggs were said to be taken annually. This record is of considerable importance as affording the most specific evidence of the existence of *Phalacrocorax bougainvillei* on this part of the coast of Peru during the middle nineteenth century.

PESCADORES ISLANDS

LATITUDE 11° 48' S., LONGITUDE 77° 15½' W.

A group of 10 islands, the outermost and highest rising 67 meters above sea level, and now of considerable importance as guano

islands. They are said by Carter to have a little dirty white recent guano, but are not mentioned by Raimondi as bearing deposits. Duffield noted an insignificant reserve of 200 tons in 1877. Forbes noted guanays, piqueros, and pelicans on all the islands not recently disturbed. At present the bird population consists mainly of guanays, with a smaller number of piqueros and at times pelicans (Anon., 1945b).

LAS HORMIGAS DE AFUERA

LATITUDE 11° 58' S., LONGITUDE 77° 44' W.

Farther out to sea, these appear flat-topped from Murphy's (1936) photograph; the highest point is 7.6 meters above sea level. They bore some guano, according to Carter (*in* Rivero, 1852) and Heiden (1887), but are apparently dangerous and difficult to work and are not now exploited. A few other unimportant islands exist between the Pescadores and Callao; Carter indicates some guano on islands off Ancon.

THE PACHACAMAC GROUP

LATITUDE 12° 19' S., LONGITUDE 76° 55' W.

This group of four islands is of some importance today and has yielded guano that has been well analyzed and is discussed in detail below. The chief island, Pachacamac, which is about 800 meters long, is said by Raimondi to have had a thin white cap, and by Heiden to have had an unimportant deposit. The modern output, however, can be as great as 15,000 to 20,000 tons in a two-year period. The islands appear to be fairly low, the highest, San Francisco, to the south of Pachacamac, being a conical rock, rounded at the top and rising to a height of 56 meters (United States Hydrographic Office, 1916a). The main birds are guanays with a smaller number of piqueros and pelicans (Anon., 1945b). Heiden mentions Punta Solar on the mainland as the site of an unimportant deposit.

ASIA ISLAND

LATITUDE 12° 48' S., LONGITUDE 76° 37' W.

The chief island of a group of six, according to Murphy rugged and irregular, with several steep hills, the highest reaching an altitude

of 123 meters, "or twice the height credited to it on the charts and the various pilot books consulted" (Murphy, 1926). There is a deep ravine cut from the highest point to a well-protected cove. The photograph given by Johnston and Platt indicates a rolling surface surrounded by a low cliff with no clear indication of any terrace levels. It is said to be much cut by the sea and to have several deep caves (Anon., 1945b). Murphy indicates that the entire seaward face, when he first visited the island, was black with guanays, but that attacks by condors caused desertion of about half the nests. Forbes also describes the guanay as being much harrassed by turkey buzzards and gulls here. Vogt (*in litt.*) thinks that predators as such are unlikely to have caused the observed desertion of the island. The photograph of the deserted breeding area looks fairly level but is described as a slope. It is probable that the declivity of the island is the main cause of the fact that though the modern production is high, it had little or no reputation as a guano island in the last century, Heiden listing it with localities having sparse, unimportant deposits and Raimondi merely speaking of "un poco de huano que la cubre."

THE CHINCHA ISLANDS

LATITUDE 13° 39' S., LONGITUDE 76° 24' W.

Three islands, with a few outlying rocks, which provided more and better old guano during the middle years of the nineteenth century than did any of the other Peruvian islands. The three islands, known as North, Central, and South Chincha, were the guano islands *par excellence*, and where no specific locality is given in any document mentioning Peruvian guano and dating from the 1850's it is probably safe to conclude that the material in question is from the Chincha Islands. In view of their importance, they have been frequently described. The following account, in so far as it relates to the old guano caps, is based on the official survey of 1853 (Castañon *et al.*, 1854; Cañas, 1854) and on the writings of Rivero (1852), Tschudi (1851, following Rivero, 1845), Peck (1854), Kinahan (1856), Habel (1871), Middendorf (1894), and Raimondi (1897), all of these authors having had an opportunity to ex-

amine undisturbed old deposits on the islands. In general Peck's account is the most detailed; he was the only observer who seems to have been aware of the scientific interest of the deposits, but unfortunately he suffered from a lack of scientific training and an undue modesty as to the interest of his investigations. "Fortunately travellers are not obliged to account for all the unexplained phenomena they meet with. I shall therefore leave the subject with the usual Spanish 'Quien Sabe?' It may have been already investigated; if not, it should be brought to the notice of scientific men as a curious inquiry.

"I wish I could see it treated by such a writer as the author of the 'Geology of the Exploring Expedition,' a work which, so far as a general reader may judge, presents splendid examples of acute observation and philosophical generalization."

No such treatment, however, was ever undertaken. Now, over 90 years after these sentences were written, it is only possible to put together such broken fragments of the picture as can be found in libraries. It is three-quarters of a century too late to write the work that Peck wished for. The priceless evidence that the deposits might have afforded has disappeared, and the present account is but the decapitated ghost of what could have been written if some geologist of the 1860's had taken Peck's remarks seriously.

The three islands are apparently composed of granite (Rivero, 1852; Murphy, 1921, rock specimen determined by Chester A. Reeds). Kinahan likewise speaks of a dark red porphyritic granite. Castañon *et al.*, and Raimondi call the rock a pegmatite. There may be some intrusive basalt if the accounts of the last-named writers, and of Peck, may be trusted. Castañon *et al.* state that a belemniferous limestone occurred at sea level on the western side of the northern island and that this was overlain by a shelly limestone containing *Ostrea* and *Balanus*, of uncertain age. There were also limestone and gypsum beds at higher levels; these were presumably of relatively recent origin. Between elevations on all the islands Castañon *et al.* describe a deposit of rounded stones cemented by felspathic sand, presumably identical with the coarse grit mentioned by Kinahan,

and overlain by shelly limestone. Murphy says that water-worn stones may still be found on the island, and figures a small outlying rock on which such stones, cemented to form a loose conglomerate, are still visible *in situ*. In an unofficial report (Cañas, 1854) of the 1853 survey, the material below the guano is described as formed of decomposed rock fragments, or sand containing small fossils; these deposits are regarded as equivalent to the alluvium of the mainland coastal belt.

The islands are surrounded by cliffs rising steeply from the sea, though there are a few sandy coves which permit landing (pl. 5, fig. 1). The cliffs are honeycombed with high, deep caves. Peck states that in places these caves form a double series one above the other. There seems, however, to be no coastal terrace as at North Guañape, but one of the sections made by the 1853 survey (fig. 16) shows indentations just above sea level which it would be tempting to regard as representing a former strand line. It is reasonable to suppose that the interior plains, well developed on the north and south islands, are due to marine planation, and that subsequent to the planation, marine sediments were deposited on the islands, which then underwent emergence. The presence of caves at sea level indicates that extensive cutting is taking place. Apparently there was cutting at a higher level in former times, giving the upper series of caves noted by Peck. The cutting at modern sea level may well have removed any other evidence of an elevated strand line, such as is now visible at North Guañape.

North Chincha Island is about 1.2 kilometers long, in a northwest-southeast direction. Central Chincha is 1.3 kilometers long in a west-east direction, but has a slightly smaller area than the northern island. South Chincha Island is much smaller, its greatest length being 880 meters.

The central parts of the northern and southern islands form relatively flat plains, or pampas, at elevations of about 30 meters above sea level. The maximum altitude of the bedrock on the northern island is given as 26 meters (31 varas) by Castañon *et al.*, which is almost certainly too low an estimate, as 33 meters by Raimondi, and as 41 meters (135 feet) by British Admiralty Chart 1323 and by Stiglich (1922). The southern island

is said to have a maximum altitude, without guano, of 31 meters (37 varas) by the 1853 survey and of 37 meters (122 feet) by the chart and by Stiglich. The central island has two elevations, at the west and northeast ends; the greatest altitude is given as 56 meters (66 varas) by the 1853 survey, as 70 meters (231 feet) on the chart and by Stiglich, and as 79.5 meters (261 feet) by Murphy, the last figure being perhaps slightly excessive, as an excellent map given by Lavalle (1918) and here reproduced (fig. 8) indicates that the northeastern hill is just over, and the western hill just under, 70 meters above sea level.

The greater part of the surface of the pampa of each of the islands was originally covered with a thick cap of guano. Kinahan, writing of North Chincha, says, "Rising gradually up from the edge of the highest cliffs (which are mostly situated at the easternmost end of the islands, . . .) are the guano beds; these latter occur as a long ridge, with lateral spurs, . . . sloping suddenly down towards the sandy bays . . . covering great part of the surface of the islands, but leaving certain headlands completely bare; the bare knolls varying much in their proportionate height and size." Middendorf compares the general appearance of one of the islands when under exploitation to a dark platter on which an enormous yellow cheese is being cut.

The most perfect indication of the form of the deposit is to be obtained from the photograph of the South Island (pl. 5, fig. 3) taken about 1860 by Capt. Charles S. Merriman of Brunswick, Maine, and published by Murphy (1927, 1936). The deposit here appears as a lenticular cap on the pampa, and there can be little doubt that Vogt (1942) is correct in describing it as having an aerodynamic profile, the form being largely determined by the wind. It is, however, probable, as is indicated below, that biological agents were also involved in determining the contour of the deposit. The less regular guano cap on the central island is well shown in the sketch published by Peck (pl. 5, fig. 2). Maps showing the areas of the guano deposits on all the islands were published by Tschudi, presumably from Rivero's study, and by Castañon *et al.* (1854; Cañas, 1854). The of-

ficial document of Castañon *et al.* also gives sections for the south and central islands. The maps (figs. 13, 14, 15) and sections (fig. 16) are here reproduced. Comparison of the outline of the map of Central Chincha with the excellent modern map of Lavalle (fig. 8) indicates that though the Commission made a better map than was available to Tschudi,

correspond well with the lengths of the lines indicating their positions on the map. It is therefore evident that the longitudinal section is reversed relative to the conventional placing of the cardinal points with respect to the observer. In redrawing figure 16, this reversal has been corrected. A comparable argument demonstrates that for the southern

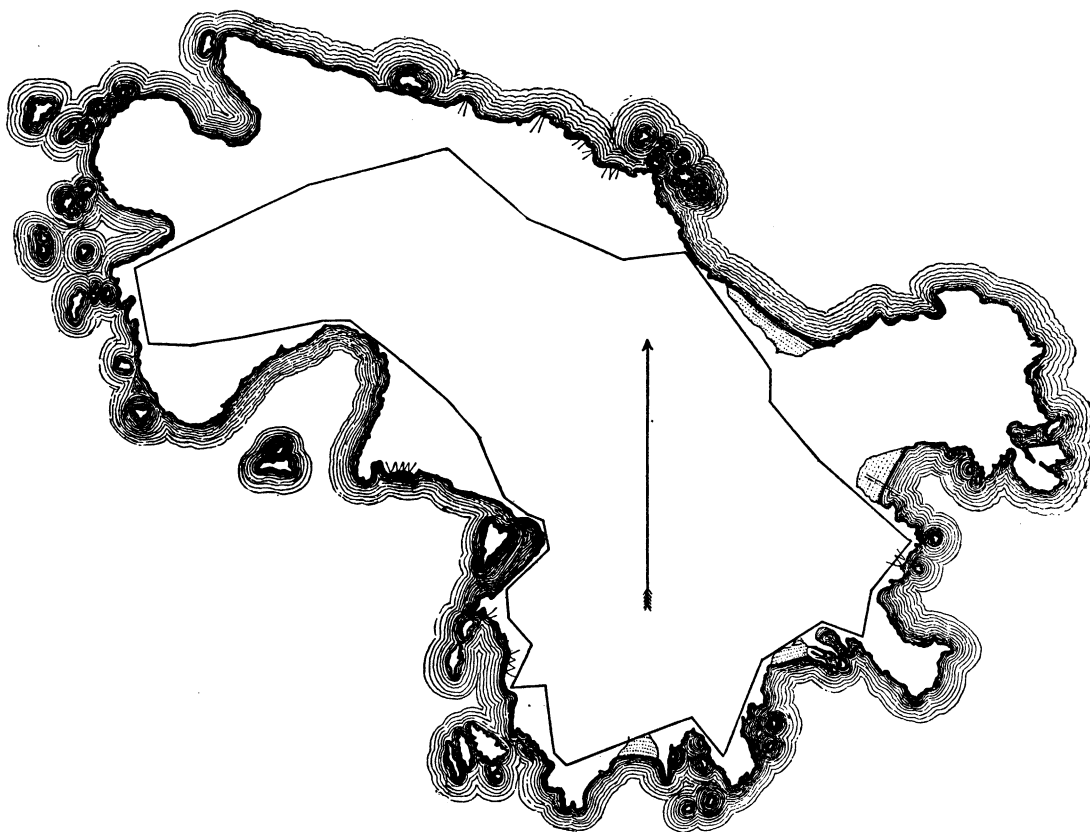


FIG. 13. Map of North Chincha Island to indicate the extent of the deposits in 1853. After Castañon *et al.*

it was still far from adequate. Moreover, unfortunate ambiguities arise in the interpretation of the sections. The longitudinal section of the central island is drawn so that if the end to the left hand of the observer be taken as equivalent to the left-hand, western end of the map, the thicknesses indicated on the transverse sections do not correspond to those on the longitudinal sections at the intersections with the transverse sections. It is reasonably certain that the transverse sections are correctly lettered, as their lengths

island section CD has been reversed, and this likewise has been corrected in figure 16. The profiles of the southern island confirm the impression given by Captain Merriman's photograph. The deposits on the central island were evidently much less regular; most of the guano lay against the southeastern face of the eastern elevation. This is apparent not only from the map and corrected section, but from the sketch given by Peck which was made in the same year as, and is in general agreement with, the survey of the Official

Commission. The western part of the island evidently had a very thin covering of guano, a covering that was apparently interrupted over the western elevation, if Kinahan's account is to be trusted. The general resemblance of the profiles of the guano caps on the Chincha Islands to those on the small islets off Lobos de Tierra is striking.

The upper surface of the unexploited

distributed. Rivero (1827) admittedly describes the white fresh guano as a product of the islands on the southern part of the Peruvian coast and says that the Chincha Islands, Iquique Island, and Pabellón de Pica yield colored guano. It is clear, however, from his repetition of von Humboldt's remarks about herons and flamingos that he had not visited the islands. Castelnau (1851), who visited

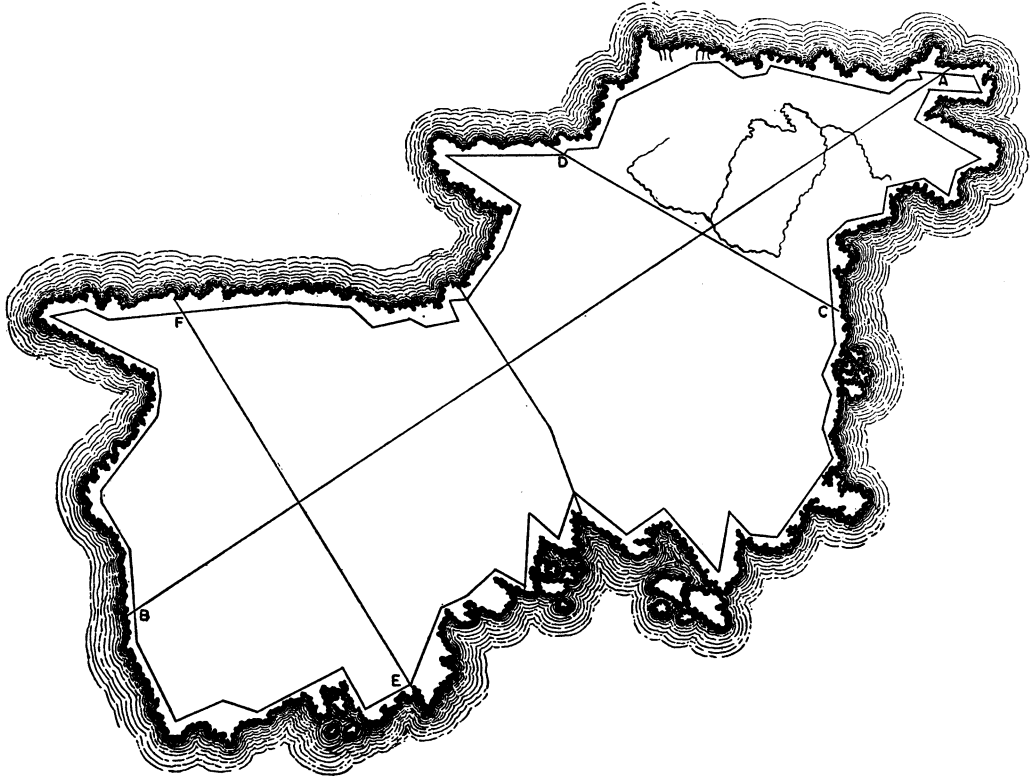


FIG. 14. Map of Central Chincha Island to indicate the extent of the deposits in 1853 and the position of the sections in figure 16. After Castañon *et al.*

guano was described by Stevenson (1825) as whitish and about a foot thick. The significance of his remarks is perhaps reduced by his erroneous statement that fresh guano is reddish, but his notes must be kept in mind in an interpretation of the findings of later observers. The reddish new guano presumably refers to the loose reddish surface layer riddled with the burrows of *Pelecanoides*, described by later authors. It is possible, in view of Stevenson's account and that of Castelnau, that early in the nineteenth century this brown loose material was not widely

the islands at the end of December, 1845, or the beginning of January, 1846, says that the superior layers are white, the next grayish brown, and the lowest of the color of ferric oxide. He speaks of the deposits having the appearance of snow from a distance. Rivero (1852) and Tschudi (1851) merely say that a layer of caliche such as occurred on otherwise exposed Chilean deposits was absent, though Rivero mentions the burrows of thousands of birds in the pure guano at the surface. The Commission of 1853 describes the surface material as extremely loose and

friable, of a dark red color, which could hardly have given the appearance of snow from a distance. In the report on the north island, Faraguet (1854) estimated the mean thickness of the friable surface layer as one-third of a vara, i.e., about 28 cm., and concluded that the presence and composition of the loose material had a negligible effect on the mean composition of Chincha Island guano as exported. Peck says that the "guano

taining feathers, eggs, and the remains of seals. The significance of the difference in thickness given for the surface material by Habel on the one hand and by the Official Commission on the other is problematical. Peck and Kinahan seem to confirm the thickness recorded by the Commission. Since the surviving photographs give no indication of a massive superficial layer conspicuously different from the rest of the deposit, Habel's

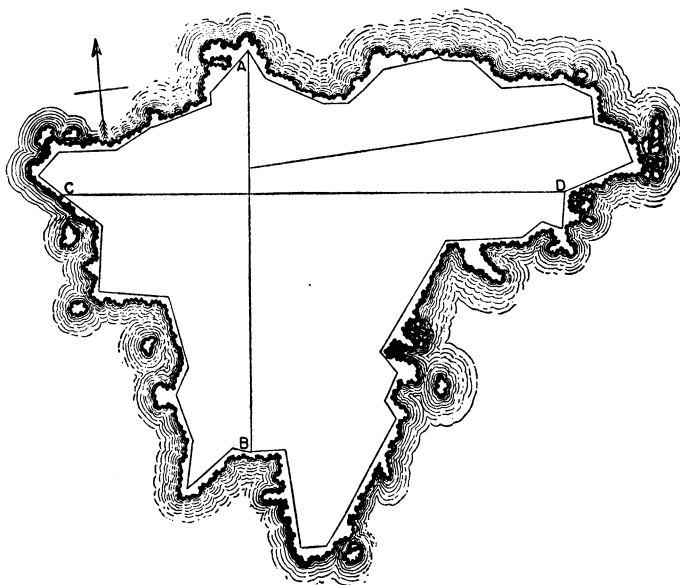


FIG. 15. Map of South Chincha Island to indicate the extent of the deposits in 1853 and the position of the sections in figure 16. After Castañón *et al.*

where exposed to the air, is of a reddish-brown, yellow color, darker than that of its general substance, where it is cut away. . . . As it is like light dry earth and full of holes, it is difficult to walk upon, there being no certainty that every other footstep will not sink in nearly to the knee. . . . A few feet below the surface it becomes compact, and from thence through its whole thickness is of nearly the consistence of Castile soap." Kinahan likewise states that at the surface the guano is generally loose and friable, and of a rich brown color. Habel indeed indicates that two distinct kinds of material composed the deposit. The upper material, known to be "three to twelve feet" thick, consisted of a homogeneous reddish brown substance con-

upper figure is certainly excessive. It is clear from Tschudi's, Raimondi's, and Kinahan's accounts, as well as from Peck's observations, that the surface layer in most places, if not throughout, was riddled with the burrows of birds, mainly *Pelecanoides garnotii*. Raimondi indicates this to have been true of the southern part of the north island and the whole of the other two islands; the absence of *Pelecanoides* in the northern part of the north island at the time of Raimondi's visit was certainly due to disturbance by the guano diggers.

According to Kinahan, the whole of the top of the deposit on the south island, still untouched when he visited the locality, was a gigantic cemetery for sea lions. He con-

cluded that the decomposing bodies of these animals rather than bird droppings were the principal materials from which the guano was formed. Raimondi indicates dead seals on the same island and notes that some are buried deeply, some less deeply, and some in the process of being covered with guano. Peck, like Kinahan, believed the dead sea lions were an important component of guano and also indicates the skeletons on the summit

undoubtedly incorrectly, that the old consolidated guano was of subaqueous origin. It is quite certain from the chemical data that bird droppings were the main constituent of all old guano samples that were analyzed, but the movement of sea lions over the deposits is quite likely to explain certain anomalies in the stratigraphy discussed below.

Below the darker, looser surface layer, the main body of the deposit consisted of a re-

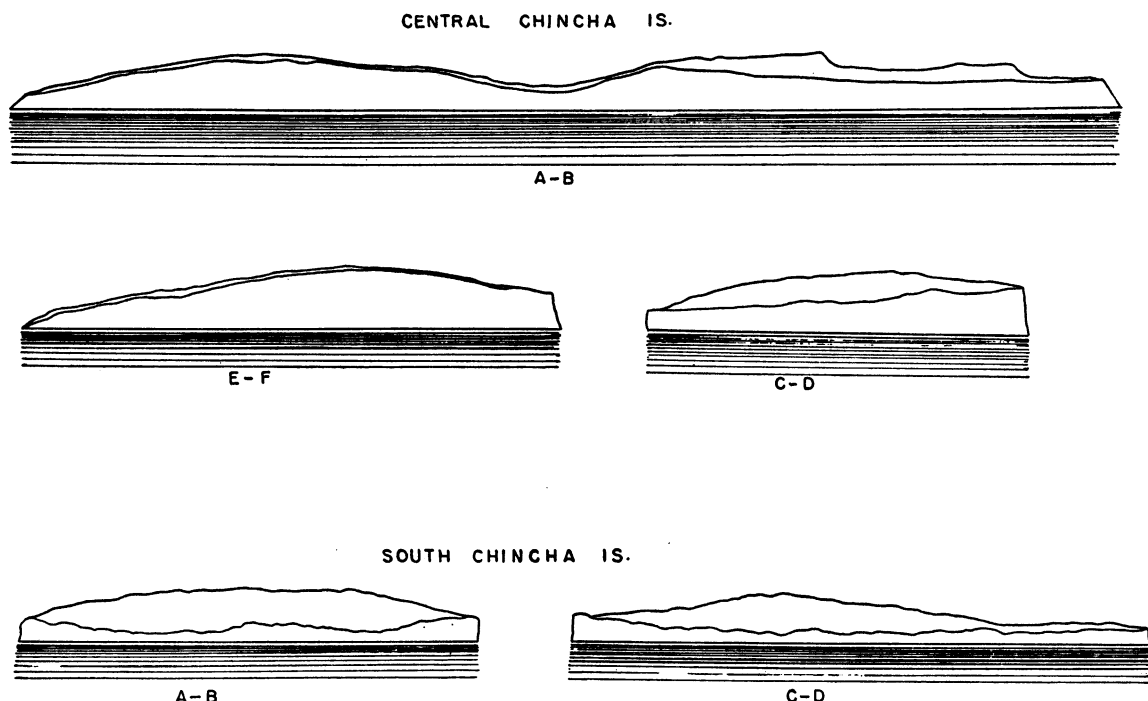


FIG. 16. Sections of the deposits on the Central and South Chincha Islands in 1853. After Castañón *et al.*

of the south island. He was informed that 15 or 20 years before his visit, i.e., between 1833 and 1838, thousands of seals might be seen ascending the slopes of the islands at certain seasons, and that old sealers frequently said they did this only as death approached. Peck intimates that he believed the form of the deposit was in part regulated by this habit. The presence of dead seals on the south island was noted at the time of Blumé and Rucker's visit in 1862 (Anon., 1863). Habel also emphasized that both seal dung and the dead bodies of these beasts and of birds were added to the bird droppings to form the superficial layer of loose guano. He believed,

markable stratified material, which at least in the lower layers could be worked only with a pick. Tschudi states that the material was grayish or whitish, but that the strata varied in color. Radiguet (1856) and Middendorf speak of yellowish material, though apparently implying that darker tints also occurred. Peck is very explicit; he speaks of "an undecided mixture of red, white, yellow, and grey, a sort of subochre, or to be very precise, about the color of white and red ashes of anthracite coal, mingled in equal proportions." This statement apparently refers to the mixed material after it had been quarried; in discussing the stratification, Peck indi-

cates a greater variety of colors. Tschudi's remarks indicate that the whitest material occupied the middle of the deposit.

All authors who examined the sections opened up during exploitation seem to have been impressed with the stratification disclosed. Though Radiguet and Habel indicate that the strata tended to follow the contour of the bedrock, it appears from the accounts of both Peck and Kinahan that they were more horizontal than was the rock surface of the island. The thickness of the strata is said by Peck to have varied from that of a "sheet of pasteboard to two or three inches." This probably implies an over-all variation of from about 1 mm. to 7.5 cm. Since Peck seems to have spent more time on the central island than on the other islands, it is probable that this observation refers primarily to the large deposit at the eastern end of Central Chincha. Kinahan says that the variation was from 1 to 6 inches, i.e., 2.5 cm. to 15.2 cm. No other authors give any estimates.

It is possible to confirm some of these statements by photographic evidence. Two photographs, taken in 1853, were published as illustrations to reprints of papers by Raimondi (1873, 1897) in the *Boletín de la Compañía Administradora del Guano* (1926, vol. 11, pp. 472, 483). These two photographs illustrate two immense blocks under exploitation on the north island. Unfortunately the original prints of these pictures cannot now be found, although Sr. Avila was kind enough to look into the matter. The published illustrations are not suitable for reproduction, but a drawing made from them is given in plate 6 (fig. 2). The guano mass shows a number of regular horizontal dark and light bands of varying thickness. There appear to be about 20 recognizable dark bands in the first photograph, so that the mean thickness of these dark and light strata taken together is probably of the order of magnitude of 1 meter. This appearance is probably due to the condition described by Peck, "in some places there is a difference in depth of color perceptible in contiguous strata for a foot or two in thickness, extending along the whole of the cuttings where they are exposed. This would include so many of the thin strata that it must have taken years, and perhaps hundreds of years, in its formation." The com-

pound nature of the bands is also rendered probable when the two photographs of this group are compared. The second one shows part of both guano masses, while only one is visible in the first picture. This second mass is nearer the camera and, though less clear, seems to show more bands than the first, though originally the two masses must have been continuous. A third photograph (pl. 6, fig. 1), in the group taken by Captain Merriman, gives an impression similar to, but less clear than, that produced by the two 1853 pictures. A fourth photograph (pl. 10), also part of the group taken by Captain Merriman, shows a guano face identified by Murphy, undoubtedly correctly, as the working on the central island. Though taken some years after Peck's visit, this photograph confirms and amplifies his account. Through the kindness of Dr. Murphy, the original print has been available for intense study. This photograph shows, throughout a large part of the guano face, evidence of fairly thick strata, which, as is indicated below, appear to be about 8 cm. thick. In the lower part of the guano face much thinner series of strata are intercalated, some of which may be as thin as Peck suggests.

It is evident from Peck's account that the strata could vary greatly in color. He writes, "the red layers were usually the thickest; but they were of all shades and succeeded each other without any ascertainable order—red, white, brownish, grayish, faint yellow, earthy white, brown, red and so on—so that I could never adopt a theory which I much wished to form, that the differently colored strata were deposits made at different seasons, year after year, for ages, and that each season had a peculiar correspondent hue on account of the periodical visits of different species of birds or of birds and seals." As far as can be judged from the Merriman photograph, the paler strata were slightly harder than the intervening darker or probably redder strata. The regularity of the alternation in the best part of this picture indicates that the dark and contiguous light band must be regarded as forming a single temporal unit or varve. The evidence that this unit is annual is discussed below.

A stratigraphic aspect of particular interest was noted by Peck but by no other ob-

server. Where the depression of "an inconsiderable valley" cut into the guano, he observed that the strata continued at nearly the same level on either side of the depression. Similarly where there were sections showing slopes covered with loose surface guano on the top of stratified guano, the strata were observed to run horizontally into the loose material, so making an angle with the surface of the deposit. As Peck realized, these conditions imply that the surface contour of the deposits had been developed later than the stratification and by some independent process. He considered that the general appearance suggested the action of water, but rightly failed to understand how water could have operated on so soluble a material without producing great changes in the chemistry of the guano. He tentatively suggests that the contours of the deposits as observed were due to the movement of vast numbers of sea lions over the guano caps, as observed in the 1830's. He also realized that the formation of the loose surface guano, riddled with *Pelecanoides* burrows, represented a process quite different from that responsible for the main stratified deposit.

As has already been indicated, a sandstone, or in places a shelly material, underlay the guano. Kinahan describes a coarse grit which, decomposing on exposure to air, became mixed with the guano during quarrying. Habel likewise speaks of sand or sandstone underlying the guano. This material is said to have been stratified; its upper part might contain as much guano as sand, while deeper down the sand increased and the guano diminished. In other places masses of guano were embedded in the sand, as were birds' eggs and bones. It appears (Phipson, 1863) that at least in some places a band of teschemacherite (native ammonium bicarbonate) lay at the base of the deposit.

Peck is explicit that he dug fossil eggs, the wing bones of birds, and the canine teeth of seals out of the bottom of the cutting on North Chincha, where the guano was 150 feet thick. This point is important, as Kinahan states that fossil eggs occurred only in the loose surface layers and believed their supposed absence from the deep layers cast doubt on the avian origin of the material. Peck also says that fragments of granite "not

waterworn, but freshly fractured, like fragments thrown off in blasting and chipping" occurred at great depths. He believed them to be too large to be the stomach stones of any sea lions now visiting the island. It is just possible that some of these stones owed their presence to pre-Columbian human visitors.

The only specific statements as to the maximum thickness of the guano beds on the three islands are those given by the 1853 survey. In the report on the northern island Faraguet gives a maximum depth of 40 varas, i.e., 34 meters, while for the same island Raimondi (1897) gives 33 meters. This figure is probably too low, as Peck mentions 150 feet as the thickness of the cutting that he examined. In the unofficial report (Cañas, 1854), the depth on the north island is given as 50 varas, which seems the most probable value and is used below. The depths for the central and south islands are given in the official and unofficial reports (Castañón *et al.*, 1854; Cañas, 1854). The mean depths given below are obtained by dividing the volume by the area, using the data of the 1853 survey. All depths are converted from varas to meters (1 Peruvian vara = 84.75 cm.).

	MAXIMUM DEPTH	MEAN DEPTH
North Chincha	42.3	12.6
Central Chincha	47.4	5.4
South Chincha	44.1	28.5

The total mass of guano on the Chincha Islands was variously estimated in the early days of exploitation. Since the external debt of the Peruvian government was covered by the guano deposits, the amount present became a political issue. The first estimation, by Don José Villa (Castelnau, 1851; Rivero, 1852) in 1842, was evidently highly inaccurate, as he arrived at the quite excessive figure of 46,632,180 toneladas (Castelnau, 1851). Peacock, in the same year (Castelnau, 1851), arrived at the still more extravagant figure of 111,530,600 toneladas. Rivero concluded in 1845 that 18,250,000 toneladas were present. In view of these estimates, the statement made in a letter on August 12, 1853, to the President of the Peruvian Republic by Don Domingo Elias, who held the guano contract at the time, that the deposits remaining ag-

gregated but 10,286,847 cubic varas, weighing about half that number of Peruvian toneladas, and would be depleted in eight years' time caused great consternation both in Peru and in Europe and led to further investigation (Cañas, 1854). A surreptitious survey was conducted prior to August 29, 1853, by a British naval instructor called W. H. McIntosh, acting under orders from Rear Admiral Fairfax Moresby (Letter No. 18, the Secretary of the Admiralty to Mr. Addington, *in* Great Britain, Parliamentary Sessional Papers, 1854¹). In his report McIntosh writes that his estimate was "exceedingly rough and imperfect, both by reason of shortness of time and the want of proper instruments, as well as a desire not to excite observation." He was apparently more concerned lest his estimate should be too low, as he continues, "To avoid the possibility of underrating the quantity, I have estimated at the rate of 40 cubic feet per ton, and have allowed a considerable excess on the measurements given by the plans and sections. . . . I have no hesitation in pledging myself that the quantity here specified is greater than absolutely remaining in the islands." The density of 0.90 employed in McIntosh's calculation, corresponding to 1.134 m³ weighing 1.016 metric tons, is a little higher than that used in the calculations of the Official Commission, but is lower than that implied by Coker (1919) for modern guano. The results obtained, namely:

	TONS (BRITISH)
North Chincha Island	5,500,000
Central Chincha Island	1,500,000
South Chincha Island	1,600,000
Total	8,600,000

are, when compared with the official survey, most notable in the low, and certainly erroneous, value given for South Chincha. The total value, in metric units, would be 8,750,000

metric tons. The conditions under which the work was done would seem to explain adequately its apparent defects.

Later in the same year, namely, on August 20, an Official Commission started work. Faraguet (1854) reported alone on the North Island; the other members of the Commission (Castañón, Asencios, Cañas, Eboli, Raimondi, and San Martín, 1854) on the other two islands. The results of their survey, given in Peruvian toneladas and also converted into metric tons, were as follows:

	TONE- LADAS	METRIC TONS ^a
North Chincha Island	4,189,477	3,860,000
Central Chincha Island	2,505,948	2,306,000
South Chincha Island	5,680,675	5,230,000
Total	12,376,100	11,396,000

^a Conversion factor of 0.921 metric tons per Peruvian tonelada as used in Faraguet (1854). Middendorf gives 0.906 for the Peruvian or Spanish tonelada.

Both Middendorf and Hutchinson (1873) express skepticism over the results of the survey. A reading of the reports, in which the methods employed are described, justifies this skepticism; Faraguet never made any deep borings, but relied on extrapolating the slopes of the bedrock obtained from exposed surfaces and shallow borings, while the other investigators were hampered by lack of instruments, though they seem to have made several deep soundings through the guano caps. Hutchinson indicates the exhaustion of the Chincha Islands in 1883 was predicted (Markham, 1862) on the basis of the survey and the current rate of exploitation in 1860, but actually occurred in 1871. One factor in this premature exhaustion, however, was the increased rate of exploitation. The statistics printed by Dancuart (1906) indicate that between 1842 and the middle of 1855 the guano was exported at a mean rate of approximately 155,000 toneladas per annum, while from the middle of 1855 to the end of 1867 the mean rate was 445,000 toneladas per annum. Since Markham used as his mean rate the export of 348,554 tons in 1860, it is obvious that, though his expectations were

¹ References to documents published in the British Parliamentary Papers, if they cannot be conveniently given under the name of the author, are cited in the Bibliography as Great Britain, Parliamentary Sessional Papers, followed by the date. The complete reference with volume number, etc., is then given, but the curious reader may still be unable to find the document in question.

too sanguine, there is also some basis for Hutchinson's criticism.

Some information can be obtained from the statistics of export. Middendorf states that 9,000,000 Registertonnen¹ were actually exported; since overloading was habitual, Middendorf concludes that actually rather over 10,000,000 Ladungstonnen were removed from the Chincha Islands. The 1853 Commission concluded that about 10% of the guano present was lost in loading. The quantity on the islands would therefore have been rather over 11,000,000 tons; English measure is implied so that the total quantity originally present in 1841 would have been, on this estimate, rather over 12,000,000 Peruvian toneladas, or about as much as was estimated to have been present in 1853 after 11 or 12 years² of exploitation.

Dancuart (1905-1906) prints the official statistics for the whole of the Peruvian guano export between 1842 and the end of 1870. The total given is 8,891,368 toneladas efectivas, of which 698,176 toneladas exported in 1870 must have included Guañape material, for, according to Hutchinson (1873), exploitation of the Guañape deposit began in 1869. Since the export figures would not include any guano used locally, they are not likely to be too high on account of inclusion of material from Guañape and other localities than the Chincha Islands. It would be reasonable to suppose that Middendorf's 9,000,000 tons represented a rounding off of the official figures. This, however, seems to be impossible, the official figures being given as toneladas efectivas, which appear (Dancuart, 1905) to represent about 1.3 times the quantity in toneladas de registro. It is to be noted

¹ A register ton is strictly a measure of volume, i.e., 100 cubic feet, or 2.831 m³. It is clear from the discussion that here, as elsewhere in the guano statistics, the word is used to imply official capacity for cargo by weight.

² Though the first contract with Don Francisco Quiros for export of guano was signed November 10, 1840, no cargo was apparently shipped until March, 1841. Twenty-three vessels with an aggregate burden of 6125 register tons were shipped before the contract was annulled on November 27, 1841, as too unfavorable to the Peruvian government, who had meanwhile discovered that in London guano had fetched a price as high as £28.0.0 per ton. A second contract, with the firm Quiróz Allier y C^a, was dated December 8, 1841. The small quantity exported in 1841 makes little difference to the discussion of the original reserve. (Dancuart, 1903.)

that in a report on export of guano from the Chincha Islands in 1850-1851, Moresby (Great Britain, Parliamentary Sessional Papers, 1854, Letter No. 18, Enclosure No. 3) says that 1 ton register "will yield at the Queen's Beam"³ 1½ tons. Moreover, another document (1853, *op. cit.*, Enclosure No. 4) gives a list of the American ships that loaded or were loading at the islands in the third quarter of 1853. In this list the burthen and the number of tons of guano are given. Considering only ships fully loaded that had set sail, the aggregate guano shipped was 17,729 tons, or 1.43 times the aggregate burthen. It appears, therefore, that Middendorf used too high an estimate of the number of register tons shipped and too low a correction factor to convert this number into actual tons weight. The best estimate for the total mass on the Chincha Islands is doubtless the official figure for output of the coast of Peru, 1842-1870, assuming small amounts not from the Chincha Islands to be counterbalanced by small local utilization. This figure should be increased by 10% to allow for wastage, giving approximately 9,780,000 toneladas efectivas; assuming, as seems reasonable, that this measure is in Peruvian toneladas, the quantity is equivalent to 9,000,000 metric tons.

Subsequent surveys appear to have been made as the guano was removed. In 1862 Frederick Blumé and M. D. Rucker made such an investigation; the results are said to have shown that 7,000,000 tons were still available on the islands (Anon., 1863). In a letter from Commander C. Sloan Stanley to the Secretary of the Admiralty (Great Britain, Parliamentary Sessional Papers, 1874a, Foreign Office, Commercial No. 10) it is stated on the authority of a Dr. Watson, formerly a medical officer on the Chincha Islands, that a mixed Peruvian, English, and American commission made a survey in 1864, but as the sounding holes were drilled prior to the survey by government engineers in the known deepest places, the estimate of the guano remaining was excessive. It is not unlikely that this survey refers to the 1862 investigation.

³ "The public standard balance kept by the Grocers' Company of London" (Shorter Oxford English dictionary).

Stanley reports that in 1874 there remained on North Chincha:

GUANO	TONS
Yellowish white	3,000
Yellow	20,000
Dingy yellow	25,000
Black	35,000
Red	10,000
Petrified	600

The nature of the petrified guano is not clear. According to de la Puente (1933), there were 2000 tons of low-grade guano on Central Chincha and 8000 tons on North Chincha in 1910. If this was leached, phosphatic material, its origin would be of some interest, but nothing seems to be known about its nature.

Cieza de Leon (1554, trans. Markham, 1864) mentions the islands in Pisco Bay as places to which the Indians used to go to make sacrifices but says nothing about guano.¹ Vázquez de Espinoza (1942), writing about 1628–1629 of his experiences in Peru at the end of the second decade of the seventeenth century, says (book 4, chap. 39, par. 1351) that it was the practice in the vicinity of Pisco to fertilize the soil of vineyards with guano. He makes no mention of the source of the material, but it doubtless came from the Chincha or Ballestas Islands. The former islands were certainly exploited during the succeeding century, as they are noted by de Ureta (1792b) as producing as much as Iquique. Von Humboldt (1806), who attributed the guano deposits to flamingos and herons and surely can never have visited the islands himself, says that the inhabitants of Chancay collected guano in boats loading 1500 to 2000 cubic feet, corresponding to about 50 metric tons of guano. There were said to have been about 50 boats involved, and these made the journey to the Chincha Islands in 20 days. If they made four trips per year, they might have collected up to 10,000 tons of guano. Not all of this, however, came from the Chincha Islands, as von Humboldt mentions Ilo, Iza (*sic*), and Aricá. Stevenson (1825) says that small boats were continually employed in carrying off guano

from the islands and that some of the cuts in the guano cap "where embarkation is convenient, are from forty to fifty feet deep." It is evident that old guano was being used but that it was taken mainly from those peripheral parts of the deposit nearest to the coves where landing is possible. Some idea of the rate of exploitation at this time can also be gained from the statistics published by Rivero (1828). Rivero tabulated, for 18 haciendas, the consumption of guano from the Chincha Islands and Ancon (presumably the Pescadores Islands), the aggregate amount being 33,600 fanegas. This tabulation is presumably the source of the statement by Tschudi that 33,000 to 36,000 Scheffeln of 250 pounds were taken annually from the Chincha Islands and other localities. Normally the fanega is 125 pounds. Rivero's data at least show that 1700 to 3400 tons of guano were removed from the Chincha and other islands in one year early in the nineteenth century before export of guano began. This is confirmed by Pickett (1848) if his testimony is independent of Rivero; Pickett says that the total annual consumption in Peru was about 3000 tons. Though Delano's (1817) remarks confirm those of von Humboldt regarding the size of the guano fleet, it is probable that Rivero's estimate rather than that based on von Humboldt's fragmentary data gives the better picture of late eighteenth and early nineteenth century consumption. In view of the known productivity of the Chincha Islands and of the fact that other islands were also worked, it is unlikely that more than 20%, and probable that less than 10%, of the annual production was removed at this period. In pre-Columbian times when balsams alone were available for collecting guano and when it seems that the material was recovered only in the winter when navigation is difficult, it may be presumed, as Murphy and Vogt have pointed out, that an even smaller quantity of guano was taken annually. The history of the avifauna of the Chincha Islands is of such great importance that it is made the subject of the greater part of a succeeding section (p. 58). Some notice of the archaeology of the islands will be taken in relation to chronological problems, but this subject is treated at greater length in a separate paper by Kubler (1948).

¹ Vogt (1942) says guano has been found in the wrappings of mummies from Paracas. This material presumably came from the Chincha Islands or other islands in Pisco Bay.

THE BALLESTAS ISLANDS

LATITUDE 13° 45' S., LONGITUDE 76° 25' W.

Three small islands in Pisco Bay, south of the Chinchas, apparently higher than the latter but with well-developed interior pampas (pl. 7, fig. 1). They were described by Peck (1854) who says the guano deposits were not so great as on the Chinchas; he found essentially the same avifauna as on the latter group. The changes that the bird population have undergone since Peck's time appear, as would be expected, to be identical with the changes at the Chincha Islands. The guano deposits, being less extensive than those in the Chincha Islands, were not exploited until the latter group was exhausted. The chief importance of the Ballestas lies in the observations made there in recent years by Vogt, already discussed, and in the fact that numerous proximate analyses of old and modern guanos are available from the group. Of other guano islands off Pisco Bay, Blanca Island is recorded by Heiden (1887) as having a deposit, while Quillos and Las Tres Marias are currently worked.

SAN GALLÁN

LATITUDE 13° 56' S., LONGITUDE 76° 30' W.

A high island, which, as has been indicated above, is not suitable for guanay colonies and which is not now worked, has apparently yielded but little guano, though Raimondi records that poor deposits occurred. Only one sample, taken at a depth of 9 feet, was a true nitrogenous guano (8.4% N). Heiden (1887) mentions meager deposits here and at Zarate Island just to the south of Carretas Point. This island is said to be flat topped with yellow streaks of guano, in the "South America pilot," and with the neighboring Zaratillo is now worked.

ISLANDS IN INDEPENDENCIA BAY

LATITUDES 14° 10' -14° 20' S.,
LONGITUDES 76° 10'-76° 14' W.

La Vieja seems to have had significant deposits (Heiden, 1887); Fallon (1899) says that 23,961 tons were estimated as present and 23,963 tons actually were removed. The island is 5.6 kilometers long and very high, rising to a peak 366 meters above sea level.

The chief guano birds recorded are potoyuncos and penguins. Vogt says that the dark color of the substratum renders the island too hot for guanays. The guano deposits seem to have been very localized, occupying but a fraction of the surface of the island. The Santa Rosa Islands to the south-east of La Vieja were probably the main source of the Independencia Bay guano that went on the market in England in the 1870's. The islands are apparently flat and low (Raimondi, 1897). Vogt says that 90% of the surface is suitable for guanays, and Forbes (1914a) indicates guanay colonies were present in 1912-1913. The very dry climate of this part of the coast permits the retention of 15% to 16% N in modern guano collected from the Santa Rosa Islands (Anon., 1945b). Fallon, however, says that the old material was much subject to modification by sea spray, and this is borne out by the existing analyses of such old guano. He records that 6006 tons of guano were estimated as present and that 3460 tons were removed. These figures may well refer to a late stage in exploitation.

ISLANDS SOUTH OF INDEPENDENCIA BAY

Though many islands exist between the preceding group and the southern boundary of Peru, none now seem to be of first-class importance, but there is some evidence that the guano production of this region was at least relatively more significant in the past. Rivero (1827) indicates that six vessels engaged in the guano trade from Mollendo, ordinarily extracting 20,000 to 25,000 fanegas per annum. These may, of course, have gone to the Chincha Islands, just as may the two barks from Chancay that brought 4000 to 5000 fanegas to that port each year. There is, however, also a specific statement that from Cocotea 6000 fanegas were obtained and from Aricá and Tarapacá 4000 to 5000 fanegas. Rivero mentions Lagarto, Animas near Ilo, Margarita, Jesús, Islay, Brava, and Mansa on the coast of Cocotea and Hornillos as islands producing guano in this region; there also seem to have been some deposits on the mainland. Jesus Island, Cocotea, Ilo, and Islay are listed by Tschudi as producing guano, who says that the small southern islands produced only white guano. Rivero

says that when birds are numerous Islay and Jesus produced annually 400 and 500 fanegas of white guano. The "South America pilot" (vol. 3) states that guano is landed for local consumption at Pacay Cove, a little to the south of Cocotea.

Farther south and now within the political boundary of Chile, certain other localities were formerly of considerable importance. The first account of the use of guano appears to be that given by Cieza de Leon (1554, transl. Markham, 1864). "Further on are the rich valleys of Tarapaca. Out of the sea, in the neighborhood of these valleys, rise some islands much frequented by seals. The natives go to them in *balsas*, and bring a great quantity of the dung of birds from the rocks, to apply to their crops of maize, and they find it so efficacious that the land, which formerly was sterile, becomes very rich and fruitful. If they cease to use this manure they reap little maize. Indeed the people could not be supported if the birds lodging on the rocks round these islands, did not leave that which is afterwards collected, and considered so valuable as to become an article of trade between the natives." This account probably refers to Iquique Island and perhaps to Patillos Island, discussed below. It was repeated, clearly from Cieza de Leon, by several later writers (cf. Kubler, 1948).

Garcilaso de la Vega (1609), in a well-known passage inevitably quoted by almost every author considering guano, wrote likewise: "En la costa de la mar, desde más abaxo de Arequipa hasta Tarapaca, que son más de dozientas leguas de costa, no echan otro estiércol sino el de los páxaros marinos, que los hay en toda la costa del Perú grandes y chicos, y andan en vandas tan grandes que son increíbles si no se veen. Crían en unos islotes despoblados que hay por aquella costa, y es tanto el estiércol que en ellos dexan, que también es increíble: de lexos parecen los montones del estiércol puntas de alguna sierra nevada." The passage continues with an account of Incaic exploitation and the strict administration of the islands, each of which was assigned as a source of supply to a province, or, if it were a large island, to two or three provinces. This seems to imply the existence of a number of guano islands. It is noteworthy that in the part of

the coast immediately northwest of Arequipa, it is stated that the crops were fertilized with heads of small fish (*cabeças de sardinas*) and with nothing else.

A third early writer, Vázquez de Espinosa (1942, transl. Clark) who was in this part of Peru around 1618,¹ writes of the district of Aricá, "all the wheat and corn and other crops are guano'd . . . 40 leagues from this city [i.e., Aricá] near Tarapacá and within sight from shore, there is a small barren island to which repair many frigates to load soil from this island; it is yellowish white, smelling like shellfish, and not very heavy; they call it guano and bring it in frigates to this city and all the ports and valleys and sell it by the fanega; it usually sells for 12 to 14 reals a fanega, and all the farmers buy it for their crops and the Indians freight it on their llamas. In fact, they would rather go without eating than without buying their guano, for with its use a fanega of grain usually yields 300, 400 or 500 fanegas. . . . And since so much has been taken from that barren island, some say that it is soil that God put there for that purpose, and others that it is the excrement of sea birds, which are so abundant along that coast that they cover the heavens; the Indians who cannot get out there go and hunt for it among the cliffs along the shore; but it has enriched many who have made a business of it with their frigates." This account almost certainly refers to Iquique. A shorter but very similar account, specifically referring to that place, is given in a manuscript, "Noticia general del Perú y Tierra Firme," written in 1630 by Francisco López de Caravantes (Jiménez de la Espada, 1881, vol. 1, app. 2, p. cxxxviii). Although Vázquez de Espinosa says that bread if kept too long at Aricá acquired a taste of guano, both he and de Ureta (1792a), writing more than a century and a half later, give the impression that this guano was imported from Iquique and was not a local product. Vázquez de Espinosa, however, mentions the enormous number of sea birds that kept dying at Aricá and attributes the unhealthiness of the city

¹ Writing of Aricá he says, "There is much idolatry because of the lack of a Bishop and the indifference of the priests. I am an eye witness of this and did something to help out by visiting in the year 1618 the Indian villages," of which a list of 16 names is given.

to this cause. His remarks on this mortality are further discussed below. Early eighteenth century travelers, however, leave no doubt as to the production of guano at Aricá on Alacrán Island.

ALACRÁN ISLAND

LATITUDE 18° 30' S., LONGITUDE 70° 20' W.

Feuillée (1714), who was at Aricá at the end of May, 1710, says that immense numbers of birds congregated on a rock and a small island close to the town, nesting there by night, "en partent tous les matins pour aller chercher leur vie." The droppings of these birds were valued as a manure which he terms guana. Warehouses had been built to store the material which was exported in ships that carried no other cargo. The material was transported to Lima and to other places on the coast, and constituted one of the best sources of the revenue of Aricá. Feuillée points out that the large rock (pl. 7, fig. 2) shut off the cooling south wind from the city. The presence of the guano filled the city with an insufferable odor which produced violent headaches in strangers and depressed the health of the inhabitants, who had a yellow appearance. He marvels at their cupidity, pointing out that they could easily have shot the birds and freed themselves from the stench of their excrement, but rather "ils aiment mieux sacrifier leur santé à un lucre sordide, dont leurs infirmités continuelles ne leur permettent pas de jouir avec la moindre satisfaction." The large rock, which is said to have been visited by the pre-Columbian inhabitants who made sacrifices there, is undoubtedly Alacrán Island, which is described in the "South American pilot" (vol. 3) as a low island joined to Aricá Head by a reef of rocks. Frezier (1716), who was at Aricá in 1713, speaks of the immense numbers of birds which he said assembled for fishing every morning about 10 and every evening about six, "pour enlever le poisson que vient à fleur d'eau dans ce temps là, ou ils font une espece de pêche reguliere." He says nothing in the text about guano, but his map shows Alacrán Island marked as Isla de Guana.

Coreal (1722), who claimed to have visited Peru between 1666 and 1697, gives a very similar account of Aricá, and his panorama of

the town from the sea is virtually identical with that of Feuillée, reproduced in plate 7. Unfortunately, Coreal is a very dubious authority. The Spanish version of his work, mentioned on the title page of the 1722 edition, seems not to be known. Although the dates of his sojourn in Peru might suggest that his observations relate to an earlier time than those of Feuillée, there can be no doubt that Coreal's account of Aricá is derived from that of Feuillée and cannot be cited as that of an independent authority.

Later de Ureta (1792a) again discussed the dangerous vapors in the city, but he implies that the guano supposed to produce them was merely stored there as an article of commerce, in transport from Iquique to various inland localities. It thus might be supposed that any old guano that there may have been at Aricá had been entirely removed, and the bird colonies dispersed, by the end of the eighteenth century. In recent decades the island has been visited only by birds, probably juvenals, moving south after the breeding season; these birds deposit guano de estacionamiento. Bird (1943) indeed indicates that the island is still guano covered and that during the removal of guano "some years ago" a number of burials were found in midden refuse. One burial was associated with turquoise and shell beads, some of the latter being made from the thick red valves of a Colombian species of *Spondylus*, formerly much prized in Peru, but not otherwise known to have been brought so far south as Aricá.

IQUIQUE OR SERRANO ISLANDS

LATITUDE 20° 10' S., LONGITUDE 70° 11' W.

Off the town of Iquique, described as a low island connected with the mainland by a causeway. The base of the light tower on the island appears to be about 8 meters above high-tide mark. The surface of Iquique Island is said to have a white appearance (United States Hydrographic Office, 1916a). The locality was an important source of guano in the early nineteenth, eighteenth, and apparently also in the seventeenth and sixteenth centuries, for in 1630 Francisco López de Caravantes specifically mentions the deposit, as has already been indicated, and the re-

ports of guano islands near Tarapacá in the works of Cieza de Leon and Vázquez de Espinosa presumably refer, wholly or in part, to Iquique Island. Rivero (1827) indicates in his first memoir on guano that what he is writing about is called in Peru "huano de Iquique ó de pajaros."

Frezier (1716), who visited Iquique in 1713, says that the island was occupied by Negro and Indian guano collectors. The guano he describes as a yellowish earth, supposed to be derived from bird droppings, "parce que outre qu'elle a la puanteur de celle des Cormorans, on a trouve des plumes d'oiseaux fort avant dans cette terre. . . ." He wonders at the fact that the deposit had not been exhausted since "depuis plus de cent ans on en charge tous les ans dix ou douze Navires pour engraisser les terres," as well as material carried off locally on the backs of mules. In spite of this exploitation the depth of the deposit was not notably abated. Frezier writes "les oiseaux de mer sont en si grande quantité, qu'on peut dire, sans exageration, que l'air en est quelquefois obscurci." He goes on to write of the birds of Aricá, and it is not absolutely certain that his remarks are specifically intended to apply to Iquique. The passage as a whole, however, is not inconsistent with the view that guanays were responsible for the Iquique deposit.

Tschudi states that the island had an area of 220,000 square feet, i.e., about 20,000 m². Castelnau gives the linear dimensions as 688 meters long and 169 meters broad. The depth of the guano was, according to Tschudi, 30 feet, i.e., 9.2 meters. Tschudi estimated the time taken to produce the deposit in terms of the daily production of a colony of half a million specimens of *Sula variegata*; this is probably a purely hypothetical population.

It has already been pointed out that at the end of the eighteenth century the Aricá warehouses were apparently filled with guano from Iquique. Rivero (1827) says that the Iquique deposit was the first in Peru to be exploited and that it was exhausted after 25 years. This lapse of time presumably refers to the period during which there was an increased rate of exploitation, over and above that prevailing from the sixteenth to some date at the end of the eighteenth centuries. The island is too close to the port of Iquique

to permit the existence of a bird colony today (Brüggen, 1938).

PATILLOS ISLAND

LATITUDE 20° 47' S., LONGITUDE 70° 14' W.

Near an inland guanera discussed below, noted by Tschudi as having once been a guanera of importance. He says that both Patillos Island as well as Iquique had been worked for 200 years, but at the time of writing yielded only fresh guano. The information relating to Iquique is doubtless from Frezier, but no authority for the Colonial exploitation of Patillos is mentioned. Thierry (1874) says that the birds had not entirely disappeared from the island and produced white guano, which was harvested with care. Raimondi (1874) gives analyses, reproduced in table 9, one of fresh guano from the island, the other of guano from "la grande ouverture de l'île" which suggests an old deposit. Even the former, it will be noted, contained only 6.14 % N.

PUNTA CHOMACHE

LATITUDE 21° 11' S., LONGITUDE 70° 10' W.

Brüggen (1938) states that on various headlands on the coast of Chile the non-breeding birds that visit the region produce guano while resting at night. Usually the deposit is small and is worth collecting only every fifth or sixth year. At Punta Chomache, however, very large numbers of *Phalacrocorax bougainvillei* produce a guano crust sufficiently thick to justify annual harvesting. Brüggen gives a photograph showing a dense population of these birds along the shore line and another of the heaps of broken-up fresh guano ready for removal.

PUNTA ANGAMOS

LATITUDE 23° 04' S., LONGITUDE 70° 31' W.

During the nineteenth century a very superior fresh white guano was collected on this point at the extreme northern tip of the Mejillones Peninsula. The material is known chemically from several analyses given below (p. 73). Brüggen suggests that the island of Santa Maria or Constitución, west of the Mejillones Peninsula, might develop a profitable colony if the birds were afforded adequate protection.

LOCALITIES SOUTH OF MEJILLONES PENINSULA

A few localities with poor deposits have been reported south of the Mejillones Peninsula. Brügger (1938) discussed these records, due to Villanueva (1878), who visited the localities in 1877, under the heading of guano blanco, but it seems uncertain that all of them were really of white new guano. There were five deposits on headlands and two on islands between Antofagasta and Caldera. One of the insular deposits, namely, Pan de Azúcar, was about 2 feet thick and contained 20% sand, 0.2% to 0.3% N, and about 18% P_2O_5 (Domeyko, 1874). On a flat area on the south of Isla Grande in latitude $27^{\circ}15' S.$, 1200 m³ of a better nitrogenous guano had accumulated, and a similar deposit of 1300 m³ existed on the adjacent mainland (Quebrada de las Torres, Morro de Copiapó). These deposits contained, respectively, 10.8% and 8.1% N and 9.5% and 11.2% P_2O_5 . Villanueva (1878) also states that a deposit mixed with sand, stones, and plant debris occurred on San Pedro Island, latitude $27^{\circ}39' S.$, south of Caldera. From the island of Guanillo to the north of San Pedro Island, he gives an analysis of a poor phosphatic guano (0.2% N, 15% P_2O_5). These two deposits were estimated as containing but 80 m³ and 150 m³, respectively.

The San Pedro Island deposit is the most southern identifiable guanera of the Peru Coastal Current region that might have received modern avian excreta. Arancibo (1938) notes from Taltal southward to Chiloe Island 27 guaneras, but the most southern of these may well be due to sea lions, for Domeyko (1874) says that on Chiloe Island caves contain pinniped guano.

CONDITIONS FOR THE FORMATION OF OLD STABLE DEPOSITS

Examination of the modern data of production indicates that while certain localities such as the Ballestas, Chinchas, Guañape and Macabí Islands had well-defined guano caps in the past and still produce considerable quantities of new guano, other localities such as Santa, Don Martin, and Asia Islands, which now are important, were of negligible significance as sources of old guano. It is very

probable that the major determinant of a stable deposit within the climatic limits permitting accumulation of nitrogenous guano is geomorphological. The old stable deposits were on islands with flat interior plains. Asia Island, which is much more rugged than the Chinchas, may be supposed to produce a good crop because it is collected quickly. This, however, is not the only determining factor. The presence of a large number of loose stones is said by de la Puente to have reduced the yield of Don Martin until they were removed. Originally this island, with Santa Island, had no bird colony, but the evidence suggests that while the surface was cleaned during the twentieth century the bird colony was initiated prior to 1852. The lack of birds may have been due partly to human interference in the early days of the nineteenth century. Vogt (*in litt.*) thinks that human interference was responsible for the negligible yields of Asia, Don Martin, and the Huaura Islands—lands that are easily accessible. Withdrawal of human activity is, however, probably not the explanation of the sudden initiation of the colony on Santa, which must at present remain unexplained.

There is a strong suggestion that the large old stable guano caps were found mainly on islands now known to be suitable for guanays, though it is possible that at least on the Chinchas Islands the last of the old guano was not produced by these birds. The association of old guano caps with present suitability for guanays is indicated by the data relating to the islets off Lobos de Tierra, Macabí, Guañape, the Chinchas, the Ballestas, and possibly also Alacrán and Iquique Islands. Many other localities, of course, now have immense guanay colonies, but such evidence as is available and has been presented above is not inconsistent with the hypothesis that most of the old guano was the product of *Phalacrocorax bougainvillei*. It also seems reasonable to suppose that the uneven distribution of birds along the coast, an uneven distribution that appears to be dependent on hydrographic factors, may in part be responsible for the localization of the old stable deposits to the northern part of the coast and to the region of Pisco Bay and Independencia Bay. In both regions persistent swirls are developed. It is also noteworthy that the rather unproductive

region south of Pisco Bay, as far south as Iquique, seems from the sixteenth to the early nineteenth centuries to have been regarded as a more important source of guano than the central Peruvian coast. Vogt (1942) disputes this conclusion, believing that Garcilaso de la Vega has been misunderstood. It would, however, seem perfectly explicit from Cieza de Leon, from Vázquez de Espinosa, and from López de Caravantes that the main source of the guano used in southern Peru in the sixteenth and seventeenth centuries was from southern islands of which Iquique was by far the most important.

The only early accounts not specific on this point are:

1. A manuscript, "Apuntamientos para el buen gobierno del Perú," written in 1564 or 1565 by Pedro de Avendaño, and quoted by Jiménez de la Espada (1881, vol. 1, app. 2, p. cxxxviii) which states that the inhabitants of the coastal regions collected and derived much profit from the dung deposited on "ciertos peñascos grandes donde duerme gran cantidad de pájaros."

2. Acosta in his "Historia natural y moral de las Indias," writing in 1580-1590, says that guano was brought from the islands to the Lunaguara Valley. Kubler (1948) suggests reasonably that this refers to the Chincha Islands.

These statements are certainly not inconsistent with a belief that the southern islands were primarily worked, though Acosta's account with Vázquez de Espinosa's indication of the use of guano about Pisco indeed suggests that the Chincha Islands were also exploited in the seventeenth century.

The only reasonable, though admittedly speculative, explanation of the decline of importance of the southern islands, a decline also clearly indicated if Rivero's first work (1827) be compared with later writings, is that minor changes in the dominant hydrographic pattern have occurred, tending to alter the distribution of the centers of abundant fish. It is indeed tempting to suppose that this postulated change was initiated during the years of hot summers and poor food supply that are recorded by Rivero as immediately preceding the year in which he wrote.

It is, however, important to remember that

such tentative conclusions do not necessarily mean that there has been a single northward progression of the zone of maximum guano production, since the prehistoric time when it lay well south of the present Chilean boundary (p. 109), or that the guanay, as the chief guano bird, has moved up the Peruvian coast for the first time in the past few centuries, as some seem to have supposed.

PERIODIC FLUCTUATIONS IN THE BIRD POPULATION OF THE GUANO ISLANDS

It is well known on the guano coast that catastrophes occasionally overtake the bird population. The adults may suddenly desert their breeding grounds, leaving thousands of eggs unincubated or chicks dying of hunger. Vast numbers of these adults may fall dead into the sea, others may appear in great flocks in Chile or even in Ecuador, and, though part of these eruptive populations may ultimately return to the islands, many perish outside their normal range. Though these occurrences are popularly attributed to a pandemic *peste*, there is impressive evidence, first marshaled by Lavalley (1917) for such an event in 1917, that the primary factor inducing the catastrophe is an abnormal extension southward and coastward of warm water, constituting in extreme cases a well-developed counter current. Lavalley's conclusions have been confirmed by subsequent catastrophes in 1925, 1932, and 1939 and are probably applicable to an earlier event of the same sort in 1911-1912. The incidence of the catastrophes during the present century, and of the abnormal rainfall which accompanies them and which is dependent on the same oceanographic disturbance, fits well with the traditional periodicity of about seven years, locally believed to characterize the incidence of heavy precipitation. Since the problem of the existence of such a cycle is raised by certain stratigraphic data to be discussed in a later section, it has seemed desirable to summarize all the available information. It is not improbable that an examination of log-books would bring to light further cases of mass mortality of birds; this, in fact, implied by Murphy (1923).

The available data on abnormal rainfall has been set out in figure 17. An arbitrary scale has been employed for Eguigúren's

records, it being assumed that each of his categories represents about twice the rainfall of the next lowest category. Sheppard's (1930, 1933) rainfall data for southwest Ecuador have been used for the period for which they are available, and the qualitative notes of other writers recording wet years in the twentieth century have been treated in the same way as Eguigüren's records, though they are less detailed. The arrows above the

Coker (1919), is incorrect on this point, for it is certain that Raimondi was on the Chincha Islands in 1853 rather than 1855. It is also apparent from the rainfall data and from the other information relating to catastrophic mortality that the neat scheme proposed by Vogt must be reluctantly abandoned. The available data are set out in the following paragraphs.

CIRCA 1618: Vázquez de Espinosa (1942)

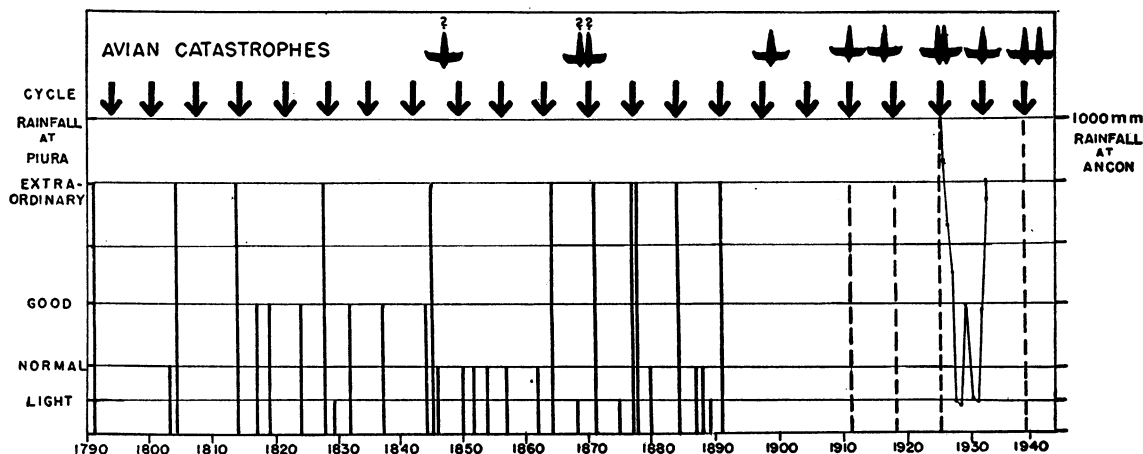


FIG. 17. Diagrammatic presentation of the Piura rainfall record, and of that for southwestern Ecuador, and of incidence of catastrophes in the population of guano birds.

indications of rainfall point to the expected incidence of rain on the basis of a cycle of 6.86 years. It is evident that this cycle may well have persisted from 1864 to 1939, though there are no data indicating abnormal rains about 1898 and 1905. Above the arrows, the inverted birds indicate the incidence of biological catastrophes or ecological depressions. Prior to 1864 there is no good evidence of the cycle. Vogt, however, believed that the cycle had persisted, with a period of exactly seven years, from 1834 to 1939. He supposed that the absence of observations of the guanay by Darwin in 1835 was due to the hypothetical catastrophe of 1834, that Tschudi overlooked the paramount role of the guanay as his visit to the guano islands, in 1842, took place the year after the next hypothetical catastrophe, that Raimondi's like conclusion was due to the hypothetical catastrophe of 1855, and Lucas' observations (p. 51) due to that of 1869. Actually Vogt's authority for the date of Raimondi's visit, namely,

who has earlier been mentioned as a visitor to Aricá in or about 1618, writes (book 4, chap. 56, par. 1415) of that city: "It is a modern foundation; Gen. Don Ordoño de Aguirre established it in the year 1600 on a pestilential and unhealthy site. It was under the shadow and shelter of a high headland or bluff at the water's edge, and enormous numbers of sea birds keep dying there; they are innumerable on this coast, and much fish and many seals die there too; and as the climate is hot, they decay at once before the vultures eat them up, and poison the air passing along the bluff and then through the city, so that the site is unhealthy." Though Feuillée, Coreal, Frezier, and de Ureta all complain of the unhealthiness of Aricá, they attribute the insalubrity to guano rather than to dead birds. It seems therefore probable that when Vázquez de Espinosa was at Aricá the bird population was suffering a catastrophic mortality.

ANTE 1827: Rivero (1827) says that while

the islands of Jesus and Islay, in years when they were frequented by many birds, produced 400 and 500 fanegas of guano, "en los ultimos años la saca ha sido muy poco." Three reasons were given for this decline in the bird population and consequently in the yield. The first was the excessive heat of recent summers, the second the scarcity of food for the birds, the third the disturbance produced by ships, notably in firing their cannon. The two first strongly suggest the phenomena of abnormal years as observed in the twentieth century. Eguigúren's rainfall data indicate extraordinary rains in northern Peru in 1814, and good rains in 1817, 1819, and 1824; the indefiniteness of Rivero's statement makes correlation with the rainfall record impossible, though it seems likely that 1824 was included among "los ultimos años" and may even have initiated the depression of the bird population. Meyen (1834) who was in South America in or about 1831 writes, in a section discussing the coast of Arica, but here referring to the "ganzen Küste des südlichen Peru," of "Pelikane . . . Scharben . . . , Cormorane und Möven . . . Ihre Anzahl ist Legionen, indem sie, un wahren sinne des Wortes, die Sonne verfürstern, wenn sie sich am frühem Morgen in meilenlangen Schaaren von ihrem Aufteuf-half erbeben." In 1845 Pickett (1848) who had been in Peru in 1843-1844, if not somewhat earlier, as United States Chargé d'Affaires, expresses skepticism as to the cause of the decline noted by Rivero and indeed seems to doubt if it had occurred. Meyen and Pickett's remarks may confirm the view that Rivero's notes refer to a temporary phase in the climatic history of the coast.

CIRCA 1848: Cookson (1874b) records that he was informed by a man who had lived 40 years at Pabellón de Pica, that when he first knew the locality (i.e., about 1834) the whole promontory was alive with birds, but that about 26 years prior to Cookson's visit (i.e., about 1848) a "plague" attacked them. They flew a league out to sea and then fell into the water, dying by the million, so that their bodies covered the beach for miles. The birds are said to have been pelicans, gannets (presumably *Sula variegata*), and "a species of tera," which may be a misprint for tern, presumably *Larosterna inca*, though the word "tera" is repeated in both English and French

versions. The account of the bodies piling up on the beach perhaps suggests less off-shore movement than is usual on this coast and may indicate cessation of upwelling, and general high temperatures.

The date is so vague that a correlation with the wet years 1844-1846 is not excluded but without supporting evidence no conclusion can be drawn. Carrey, writing in 1875, also mentions the catastrophe as having occurred 30 years before, which, if the statement be acceptable, would indeed fix the date as 1845, but it is probable that Carrey's dating is approximate and is derived from Cookson.

CIRCA 1869-1871: In striking contrast to the accounts of the abundance of birds on the Chincha Islands in the 1850's Dr. Frederic A. Lucas, in a statement written for Murphy (1925), says that in 1869 there was but a small gathering of gannets on a cliff at the northwestern corner of Central Chincha. No birds occupied the pampas of the islands, none occurred on Blanca islet or even on the Ballestas Islands. Occasional pelicans and penguins were noted in the region, but apparently no guanays. Turkey buzzards were absent, though Kinahan (1856) had specifically noted their presence at a time when birds were abundant.

This depopulation was doubtless largely due to human interference, but there is some evidence of a catastrophe just about this time or perhaps a year or two later. Cookson (1874b) says that an English engineer called Hindle had informed him that some years since, on reaching one of the northern islands, either Guañape or one of the Lobos group, he had found the surface of the island covered with dead gannets and a species of diving bird, presumably *Sula variegata* or *S. nebouxi* and *Phalacrocorax bougainvillei*. There is independent evidence that Hindle was at Guañape and the Lobos Islands in 1871, as he is described as an engineer engaged to survey these islands. Stanley (1874) says that competent engineers surveyed Guañape in 1871, while a note in Nature (Anon., 1872) indicates that in January, 1872, news of a completed survey of the Lobos Islands had just reached England. Cookson adds that the rapid disappearance of birds was well known on

the coast, and at the time of writing (March, 1874) there were noticeably fewer birds than had been present eight years previously. It is reasonable to correlate Hindle's observations with the abnormally wet year 1871, but in view of Lucas' account it is apparent that the general reduction noted by Cookson had begun before 1869 and was not entirely due to abnormal meteorological conditions.¹

1891: No observations on the mortality of birds during the excessively wet season of 1891 are apparently available. The accounts collected by Murphy (1925, 1926, 1936) indicate a great destruction of marine organisms, the appearance of tropical animals off the normally temperate Peruvian coasts, and other biological anomalies, so that it is hardly conceivable that the guano birds were unaffected.

1899: Murphy (1923) states that Rear Admiral C. F. Goodrich informed him that on August 10 and 11, 1899, the U.S.S. "Newark," under his command, passed for 300 miles through areas of dead pelicans and other sea birds off the northern coast of Peru. At noon on August 11, the ship was in latitude 5° 07' S., 45 miles from the coast.

1911: Forbes (1914b) reports that in November, 1911, "almost the entire avian population of the Chincha islands began suddenly for some reason, so far not yet satisfactorily explained, to take their departure, leaving both eggs and young to their fate; some to die of hunger, others to be devoured . . . by the Vultures, the Gulls and the Terns. By December 1911, hardly a score of birds remained." Though the population apparently started to return in February, no breeding occurred until the end of 1912. The exodus and consequent loss of the brood were also observed at almost every other breeding station throughout the coast of Peru. It would appear, however, that the catastrophe did not affect all regions synchronously, for as late as May and June, 1912, Forbes observed many dead birds floating in the sea at Lobos de Tierra Island.

Forbes was at a loss to explain the emigration and mortality. He concluded that since

birds returned to the Ballestas and Chincha Islands in February, it was improbable that failure of food supply was involved. Moreover the seal population showed no signs of leaving the islands, which he supposed would have happened if no fish had been available. Inasmuch as Forbes did not consider either possible movements of the fish population or differences in the species hunted by birds and seals, these arguments are fallacious. He observed in 1912 that small earthquake shocks caused temporary disturbance of the colonies and suspected that the emigration was due to more violent shocks scaring the birds away from their breeding grounds. No evidence that earthquakes had occurred at the time of the emigration was given. The only records of any environmental abnormality are the statement by Bowman (1916) that in October, 1911, heavy rains occurred in Peru, and Lavalley's remark about aguaje noted below.

1917-1918: The next catastrophe took place in March, 1917, and was investigated by Lavalley (1917). Inasmuch as the young birds were able to fly by the time of the disturbance, the mortality was said to have been less than on previous occasions. The only previous occasion specifically mentioned is November, 1912, which is apparently an error for November of the summer 1911-1912; and in another part of Lavalley's paper, he states that aguaje was observed in December and January, 1912, evidently again meaning December, 1911, and January, 1912. Abnormal mortality was noted in March, 1917, at Guañape Island, in the Pescadores group, at Cabinzas Island, and at North and Central Ballestas Islands. Numbers of dead birds were cast ashore at Supe, Huache, and Callao. In some places, moreover, birds, though not dying, were observed to be debilitated and to be suffering from inanition. A definite southward movement was noted in some localities; on March 14, pelicans arrived at Guañape from the abandoned Lobos Islands, while birds from Cabinzas Island moved south to Asia Island, and to Pachacamac Island. Coincident with this movement a southward-flowing warm current was noted at Guañape, Huaura, and the Pescadores Islands, and aguaje was observed in late March and early April. Lavalley concluded that the effect of

¹ It is possible that the wetness of the Guañape guano imported in 1871 into England (Voelcker, 1872) reflects the abnormal rainfall at this time.

the warm water was to destroy plankton and to cause a withdrawal of the fish population. Such birds as suffered from any disability would be unable to migrate southward, and the lack of food would render starving birds peculiarly liable to disease. One-third of the dead birds that were examined were found to be infected with *Aspergillus fumigatus*. Vogt quotes Basadre (1940) as indicating that 1918 was a climatically abnormal year, but Lavalley's observations apparently indicate that 1917 was ecologically unfavorable also. As is indicated below in the discussion of the variation of the total yield of guano, there seems to be evidence of a continued decline in the population during both 1917 and 1918.

1923: Lavalley (1924) has described mortality of guano birds during May and June, 1923, correlated with abnormally warm weather and supposedly due to the influx of warm water restricting the plankton and the anchovetas to layers too deep for the birds to reach. This occurrence has been further discussed by Gunther and by Schweigger. Gunther supposes, no doubt correctly, that convergence of the warm tongues of his anticyclonic swirls would give rise to aguaje and other unfavorable conditions at any time that it occurred. Schweigger indicates that Lavalley's observations apparently constitute a case of the phenomena also observed in 1930, 1934, and 1939-1941, when movement of warm water towards the coast during the autumnal months was established by hydrographic observations. The autumnal counter current is doubtless generated in the same way as the more impressive counter current of the first three months of the truly abnormal years, but coming after the main breeding season and affecting a relatively limited part of the coast, it may cause little or no damage to the guano birds. Señor Avila assures me (*in litt.*) that 1923 is not to be regarded as an abnormal year.

1925: The late summer, from January to March, of 1925 was perhaps the most abnormal yet recorded on the Peruvian coast. It has naturally been discussed by various writers, but for the present study the most valuable account is that given by Murphy (1926), who fortunately was in Peru at the time.

During the first two weeks of the year con-

ditions were normal. About January 18, a sudden rise in surface temperature took place in latitude 5° 45' S., and during the succeeding days the temperature continued to rise, till on January 27 it had increased from about 19° C. to about 25° C. Rain began to spatter at Talara, in this latitude, on January 19, and by January 27 fairly heavy and constant precipitation had begun. At Callao the water temperature rose to 26.7° C. during March, and as far south as Valparaíso quite abnormal surface water temperatures, up to 21° C., were reported. During April and May the coast gradually returned to normal. Murphy gives evidence that the highest water temperatures were not observed in the most northern localities. This indicates that the warm water cannot have been derived from a narrow coastal current of the true Niño type but must have moved in towards the central Peruvian coast from the oceanic region to the northwest. Current observations indicated a definite movement setting south, and various tropical fish appeared in the normally temperate inshore waters of the coast.

Sick and dead guano birds were numerous in northern Peru by the end of January, and during March the lighters at Callao and Salaverry were full of emaciated birds. Thousands of carcasses lined the entire coast. Dexter (*in* Walcott, 1925) states that the breeding birds deserted the Lobos and Guañape Islands in March, and (*in* Murphy) writes that millions of cormorants appeared about Valparaíso, the Choros Islands near Chañaral, and Alacrán Island near Arica. Never before had so many birds been seen resting on the mooring buoys of the Chilean ports. Murphy notes specifically that the catastrophic mortality did not affect *Fregata magnificens* Matthews in northern Peru, and that while certain subantarctic petrels normally present on the coast in late summer did not appear, tropical birds such as *Sula dactylatra* Lesson and *Phaeton aethereus* Linnaeus were met with south of their normal ranges. Murphy (1936) records that small flocks of guanays appeared in quite abnormal situations, which were by no means all to the south of the normal range of the species. Thus these birds were noted in various parts of the Gulf of Guayaquil and even far up the Río Guayas. The irruption onto the coast of Chile was, however, clearly

even more remarkable. In addition to the notes by Dexter, referred to above, Moore (1926) indicates that even before the rains began in northern Peru, hordes of hungry guanays came ashore at Coquimbo, apparently searching for food among the cattle and swine. At San Antonio at least 20,000 birds were observed dead or dying, and others were noted pushing southward. Moore concluded that the influx onto the Chilean coast consisted of millions of birds.

1926: Sheppard (1930, 1933) noted that the rainfall of 1926 in southern Ecuador, though not so high as in the previous year, was still abnormally great and that exceptional movements of birds onto the Ecuadorean coast again took place.

1932: Sheppard (1933) states that the next wet year in southwestern Ecuador was 1932, and that again abnormal movements of birds, not noted since 1926, occurred. The movement was first apparent in May and was at its height between June 7 and June 9. Hundreds of cormorants were stranded in the city of Guayaquil. Thousands of birds were observed flying in a northward direction along the coast, and dead or dying birds littered the beach. Most of the individuals were guanays, but many *Sula variegata* were observed as well as a small, smoke-colored sea bird that Murphy identifies as *Puffinus griseus* (Gmelin), and a few pelicans. Murphy (1936) also quotes information from A. Hyatt Verrill (*in litt.*) that guanays reached latitude 3° 55' N. on the Colombian coast in this emigration.

1939-1941: In 1939, a year of high water temperatures and some rain in northern Peru (Schweigger, 1940), very abnormal movements and mortality of guano birds occurred (Vogt, 1941). The previous season had been remarkable for low water temperatures, but by the end of October, 1938, it was apparent that an exceptionally fast increase in temperature was occurring. This does not appear to have affected the birds adversely until the late summer, but in April virtually the entire population of Lobos de Tierra left the islands, and at about the same time *Sula nebouxi* appeared at the Chincha Islands. There seems to have been rather unusual fluctuations in the bird populations of the intervening islands still earlier, but these did not take the form

of wholesale desertion until late in the season. The abandonment of the more northern islands at first led to a gigantic concentration of birds on the Chincha Islands, which acquired a population of the order of 11,000,000 guanays by June 5. Five days later the islands were virtually deserted, and reports of abnormal movements onto the Chilean coast were received in Peru. The southward movement brought birds at least as far south as Chafñaral, and as on previous occasions there was also a movement northward. In July dead birds were reported in various localities. It seems probable that about 90% of the guanay population left the Peruvian coast, and the mortality in this emigrant part of the population was undoubtedly very great.

The succeeding year was by no means normal. Desertion took place on various occasions on the Chincha Islands; on February 11, 1940, about three-fourths of the guanay population abandoned the islands. On Santa and Blanca Islands, regions not usually occupied by guanays were used as nesting sites. This is probably to be attributed to abnormal wind directions.

In 1941 mass mortality was very marked and was again accompanied by high water temperatures (Schweigger, 1943; Fiedler, Jarvis, and Lobell, 1943). As is indicated below, both Schweigger and Fiedler, Jarvis, and Lobell came to the conclusion that there was no real dearth of anchovetas during the late summer of 1940-1941, but that owing to the movement of warm oceanic water over the top of the cooler, plankton-rich, coastal waters, the fish tended to remain, at least by day, at inaccessible depths. The succeeding year, 1942, appears to have been normal.

Señor Avila (*in litt.*, July 8, 1946) kindly informs me that since 1941 there has been a very slow but definite increase in the bird population and that 1946, which might, on the basis of a seven-year cycle, be expected to be abnormal, had proved to be a normal year. No catastrophic decline occurred in the later part of the summer of 1946-1947 (Anon., 1947), or in later years up to 1949.

The data summarized for the individual years suggest that the worst catastrophes occur at times when a very large quantity of warm water moves from the northwest towards the coast. The incidence of such catas-

trophes, taken together with the rainfall record, certainly suggests a periodicity of about seven years, of the kind already discussed. It is, however, apparent that relatively minor disturbances late in the year can cause mortality, as in 1923, while the results of very marked hydrographic disturbances such as those that began in October, 1938, may not begin to be apparent in the bird

are worked in alternate years, and irregularities in the sequence of rotation have been frequent. Nevertheless the curve confirms the existence of catastrophes in or about 1911, 1917–1918, 1925–1926, and 1939–1941. The expected reduction in 1932 is, however, not indicated. In the curve as published by Vogt and in the thirty-sixth Memoria del Directorio de la Compañía Administradora del

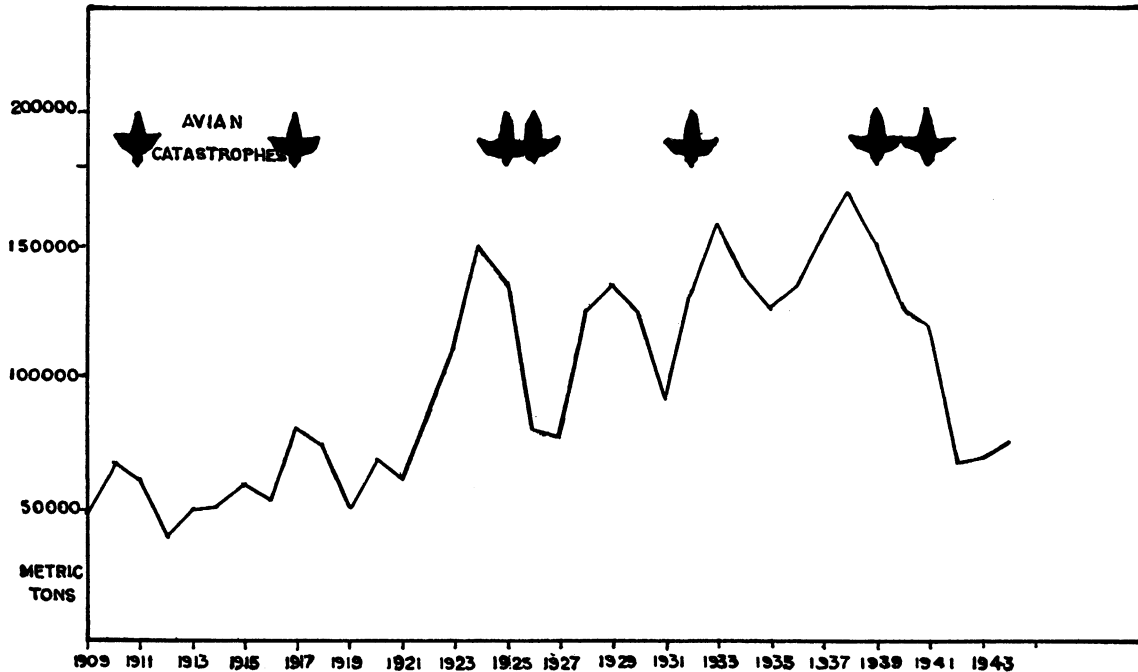


FIG. 18. The annual yield of Peruvian guano.

population until some months later. The separation of markedly abnormal years from the others may therefore be a little arbitrary, unless there is a very large amount of data relating to all phases of the abnormality, as exist for 1925 and 1939.

Some further information can be derived from the curve (fig. 18) showing the variation with time of the total yield of all the guano islands. This, following Vogt, may be calibrated as a population curve, assuming one adult bird to be responsible for 15.8 kilos of guano per year. The calibration is of course very imperfect,¹ as the majority of islands

Guano, there is a decline after a maximum in 1929–1930. This would correspond to a reduction in the population in 1930. Vogt thinks that changes in the administration of the company at that time led to changes in the rotation of guano collection of the various islands and that the minimum is meaningless. Schweigger (1943) believes that since there was a marked movement of warm water onto the coast in the autumn of 1930,

¹ In December, 1939, at the depth of a depression, an aerial photographic survey (Vogt, 1940) indicated 4,421,750 guanays on the islands, other than the Chinchas, which do not seem to have been entirely deserted

at the time. The yield of guano for 1940 was 125,637 tons, which would correspond to 7,900,000 birds on the basis of Vogt's conversion factor. It is probable therefore, as would be expected *a priori*, that the 1940 yield is too great as a measure of the population, because it includes material (e.g., from the Pescadores, Asia, and Chincha Islands) deposited prior to the beginning of 1939.

this year may have exhibited some of the characteristics of an abnormal year. Actually reference to the statistics of guano production shows that the position of the point for the collecting season 1930–1931 on the graph given by Vogt and in the publications of the Compañía Administradora does not correspond with the data given for the output (e.g., in the thirty-sixth Memoria). Assuming that the statistical summary rather than the curve is correct, the decline in population appears to have taken place in 1931 rather than 1930. It is, however, not impossible that Vogt is correct in thinking that the 1932 minimum is obscured by the rotational¹ system. It is also possible that the other features of the part of the curve that relates to the 1930's, namely, a maximum for 1933–1934 and a subsequent weak minimum for 1935–1936, may be due to irregularities introduced by the same cause. It does not seem possible to analyze the changes in the 1930's more effectively, and the only conclusion that can be drawn is that during most of the period for which data exist the curve of guano production is in fair harmony with the other information relating to fluctuations of the bird population.

The Compañía Administradora del Guano has also kept records of the reports of the presence or absence of food, primarily shoals of *Engraulis*, as observed by the guardians of the various groups of islands. Their data, presented as percentages of observations reporting the presence of food, have been published by Fiedler, Jarvis, and Lobell (1943). Since 1933, reports have been received from 15 stations, but prior to that date the records are far more complete for the northern than for the southern islands. No returns, unfortunately, are available for 1925. Owing to the overweighting of the northern islands in the earlier years the means for the whole coast are not equivalent through the period. The longest runs available, however, can be divided into three groups. For the two Lobos Islands, Macabí, and the two Guañape

Islands, the returns are almost complete from 1918 to 1940. The data from these localities are presented in the top section of figure 19. There is obviously great variation due to local factors. This is particularly evident when the data for the two Guañape stations, which are very close together, are considered. The mean curve, however, gives very clear indications of three periods, 1918–1925, 1925–1932, 1932–1939, in accord with the climatic variation already discussed. This is particularly striking if it be remembered that the abnormal year 1925 would almost certainly have proved a very definite minimum. For the more central islands only Mazorca and the Pescadores Islands have long enough runs of observations to be of any great interest. The variation of the mean curve is obviously less likely to be significant in this case than where five localities are available, but it is clear from the middle section of figure 19 that the same general pattern is implicit in the variation here as around the northern islands. For the southern islands, only the Chincha record extends back before 1924; it has been used in the lower section of figure 19 in conjunction with the next most northern stations, Asia and Pachacamac, for which observations began in 1924 and 1926, respectively. The mean curve after 1926 shows no clear indication of two periods divided at 1932.

This geographical variation in the cyclical pattern is not unexpected. It is reasonable to suppose that in so far as the variation in available food is controlled by the movement of warm water down the coast from the north, the more northern islands would show the effect more sharply than the others. It is clear, however, that other factors are also involved. The percentage of positive observations off the Chincha Islands is strikingly high between 1920 and 1927 (omitting 1925), in no case falling below 97.7%. In all subsequent years it is much lower, surpassing 90% on only one occasion (91.7% in 1937). Such a striking change can in no way be attributed to the cyclical cataclysms separating the periods of the mean graph for the five northern stations. The only hint of the meaning of this change, if it be other than an increase in the objectivity of the wardens making the reports, is to be derived from Schweigger's

¹ The output for Guañape, which had not been worked in 1931–1932, was 20,869 metric tons in 1932–1933, which is rather low for this island. The high yield of the season may be due to the fact that Guañape, Don Martín, and the three Chincha Islands were all worked; thus more productive islands may have been selected than in the previous season.

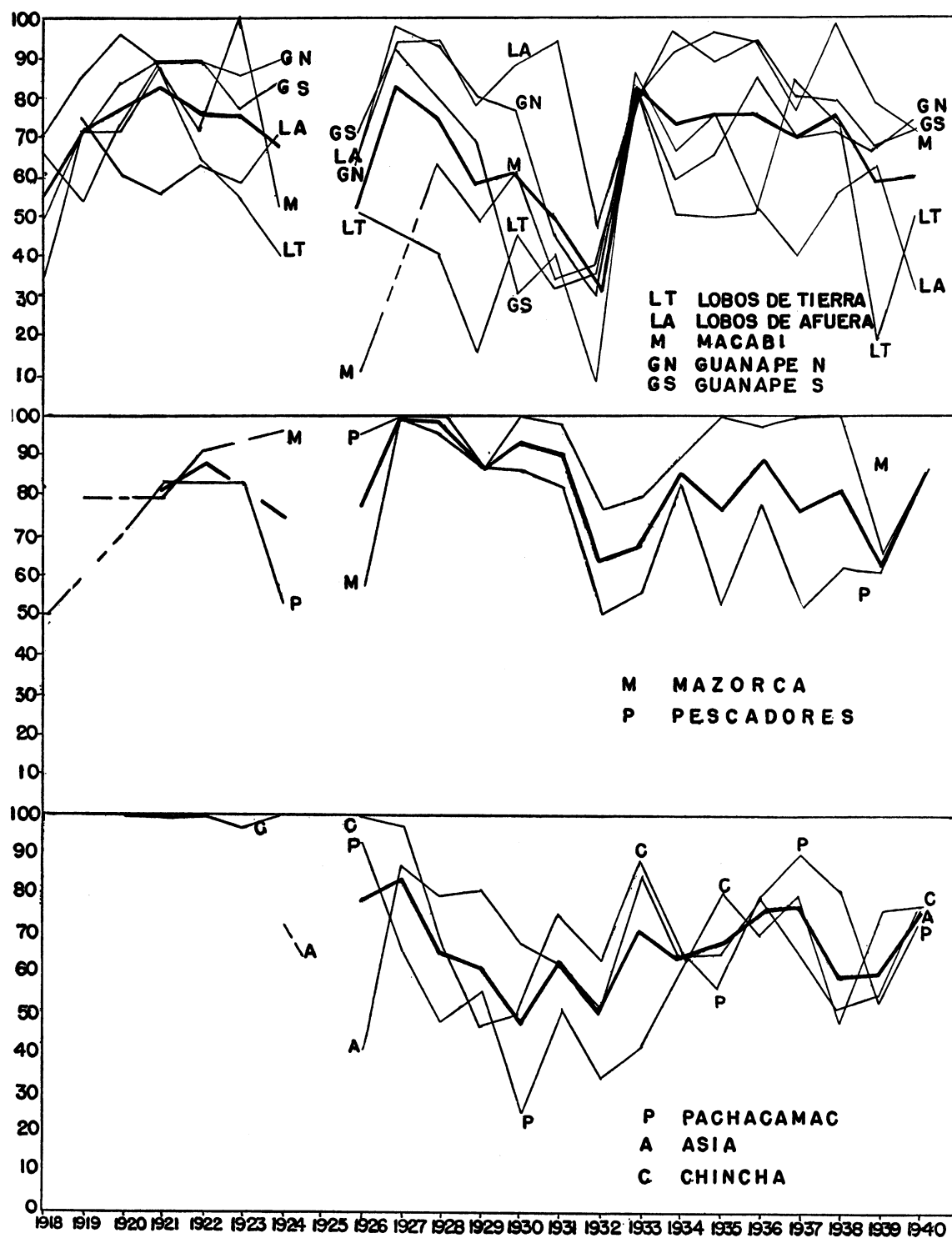


FIG. 19. Percentage of reports of the guardians of the islands that indicate the presence of food fishes. Modified from Fiedler, Jarvis, and Lobell.

map showing the distribution of regions of abundant shoals of fish. No marked evidence of exceptional productivity is indicated, though from the importance of the Chincha Islands as bird colonies and the high incidence of reports of food before 1927, one might have supposed that very rich fishing grounds have existed in their neighborhood. It is reasonable therefore to suggest that since 1927 some change in the circulation, presumably involving the swirl that seems to exist in this region, has taken place, and that the present rather low productivity of the region is of comparatively recent origin.

There appears to be considerable uncertainty as to the causes of the variation in the supply of food. Two hypotheses have been proposed. Vogt (1942) believes that there is a real deficiency of *Engraulis* in Peruvian waters at the time of the minimum. This he attributes mainly to the migration of the fish southward and out to sea. He concludes from a study of a sample collected in 1942 that the last good year class had been that of 1938–1939; in the next two years the fish are supposed to have been away from their normal breeding grounds. Del Solar (1942) supposes that an increase in predatory fish also contributes to the deficiency in the anchoveta population.

Schweigger (1943) follows the second hypothesis, namely, that there is no real deficiency in the *Engraulis* population but only an apparent scarcity, the major part of the fish remaining in deep cool water, at least by day. As evidence for this view he indicates the presence of anchovetas in the guts of predatory fishes in regions in which they seem to have disappeared from the surface water. He supposes, as Lavalle had done, that when an incursion of warm unproductive water occurs, the fish tend to remain with their planktonic food supply beneath the thermocline that develops under such conditions. Fiedler, Jarvis, and Lobell (1943) also give evidence pointing in the same direction. During February and March, 1941, when the water temperatures exceeded 20° C. they encountered small shoals on eight occasions by day and two occasions by night. The only large shoals encountered were three at night. On one occasion at night an area of 200 square miles south of Mazorca Island was

filled with the fish, which disappeared the following day. The guano birds, which feed normally only by day, were abandoning their nests in search of food in spite of this nocturnal plenty. During July and August, when the water temperatures were under 20° C., Fiedler, Jarvis, and Lobell encountered small shoals on three occasions by night, but none by day, and medium and large shoals on six occasions by day, and on three occasions by night. The number of observations is small, but so far as it goes the evidence suggests that when the water temperature lay over 20° C. at the surface, the *Engraulis* population, perhaps aggregated into a few immense groups, were performing a good deal of diurnal vertical migration, ascending into the warm surface waters by night when the birds were unable to feed on them. As the warm counter current withdrew, the large anchoveta shoals remained at the surface by day and were available as food, though it appears from Schweigger's work that some diurnal migration always takes place. Fiedler, Jarvis, and Lobell also consider that shoals in vigorous movement may not constitute available prey for the birds and that even when small shoals were observed at the surface in February and March they could not necessarily be captured. This factor they believe further reduced the food supply in 1941. It must be noted that Vogt (1942), who was working on the guano coast at the same time as were both Schweigger and Fiedler, Jarvis, and Lobell, evidently knew of the general conclusions that they had reached but remained unconvinced of the correctness of these conclusions. He points out that not merely is the positive evidence for the presence of *Engraulis* in deep water meager, but if they are available at the surface only at night during the minima, as has been supposed, the pelicans should be little affected, which is obviously not the case. It is clear that far more quantitative work on the problem is needed.

QUALITATIVE HISTORIC CHANGES IN THE AVIFAUNA OF THE GUANO ISLANDS

When the chronological problem in the succeeding section is dealt with, it will be of importance to have information on the qualitative changes in the bird population of the guano islands during the past 200 years. The

fundamental contribution to this subject was made by Coker (1919), but Murphy added further records, and a little more material has come to light in the preparation of the present account.

The oldest record of the specific nature of the avifauna of a Peruvian coastal islet is a pre-Incaic ceramic, which Professor Kubler informs me was certainly made on the northern part of the guano coast. This vessel is in the collection at Hacienda Chiclín; I owe the photograph of it (pl. 8, fig. 1) to the kindness of the curator, Sr. Rafael Larco Hoyle, and of Professor Kubler. It has been briefly mentioned by Vogt (1942) and shows an islet with piquero nests on the cliffs and what may be guanay nests on the interior plain at the top. Two balsas are moored or beached at the base of the cliff, and the piece might be regarded as an illustration of Carter's remarks on El Pelado (p. 32). The nests on the pampa of the island are clearly meant to be different from those on the cliff; they might perhaps be pelican nests but seem more likely to be those of the guanay, to which Murphy referred them on being shown the photograph. It is, of course, possible that the men who landed from the balsas were intent on obtaining guano rather than birds or eggs. All the detailed evidence already given relating to the agricultural use of guano in early times comes, however, from the southern part of the guano coast.

The first specific literature reference to a guano bird seems to be that of Juan and de Ulloa (1806) who wrote of conditions not later than 1748. "The lands in the jurisdiction of Chancay, like the other parts of the coasts of Peru, are manured with a dung of certain sea birds, which abound here in a very extraordinary manner. These they call Guanoes and the dung Guano, the Indian name for excrement in general. These birds, after spending the whole day in catching their food in the sea, repair at night to rest on the islands near the coast, and their number being so great as entirely to cover the ground, they leave a proportionable quantity of excrement or dung. This is dried by the heat of the sun into a crust, and is daily increasing, so that notwithstanding great quantities are taken away, it is never exhausted."

A little later de Ureta (1792a) wrote of

"páxaros nombrados Huanaes que hacen su residencia fija en el Puerto de Iquique." Later records relate mainly to the Chincha Islands, in a part of the coast between Chancay and Iquique. These records may be conveniently considered together, and then such nineteenth century notes as were not included in the preceding account of the other islands will be summarized.

In 1825 Stevenson wrote of the small islands in Pisco Bay, that is, of the Chincha and Ballestas Islands: "A species of birds frequenting these islands in great abundance is called Huanay: hence the original name of the matter now used as manure. The bird is of black plumage, is as large as the seagull, and breeds during the whole year, with this peculiarity, that each nest, being only a hole in the huano, contains a fledged bird, an unfledged one, and one egg." In spite of Stevenson's rather fanciful ideas as to the reproductive cycle, and his inverted etymology, there can be no doubt that he is referring to *Phalacrocorax bougainvillei*, and there is no reason to suppose that Juan and de Ulloa or de Ureta meant any other bird.¹ Meyen (1834) in a passage quoted earlier (p. 51) speaks specifically of cormorants as well as pelicans, using in fact two words (Scharben, Cormorane) which could refer to *Phalacrocorax*, in great numbers on the coasts of southern Peru. His account strongly suggests the guanay. It thus appears that in the eighteenth and first quarter of the nineteenth century, the chief guano bird was *Phalacrocorax bougainvillei*, as it is today.

Tschudi (1846b), who was in Peru between 1838 and 1842, considered that the most important guano bird was *Sula variegata*, which he says breeds on the sand and which he clearly thought responsible for the deposit on the flat island of Iquique. He lists, however, *Phalacrocorax gaimardi*, *P. bougainvillei* (sub

¹ It is, however, possible that the words *huanae* or *guanay* were used as an inclusive term for all guano birds; Boussingault (1860b) indeed so employs the former word. The color and size indicated by Stevenson are adequately diagnostic and the notes given by Carter (in Rivero, 1852) clearly employ the word *huanae* as a specific designation. Boussingault was on the Peruvian coast in 1832 and beside pelicans he thought he saw primarily the flamingos and herons that von Humboldt, and Rivero (1827) in his first memoir, so unfortunately regarded as important guano birds.

albigula), and *P. olivaceus* (sub *Plotus anginga*; cf. Murphy, 1936), *Pelecanus o. thagus*, *Rynchops nigra*, and *Larus modestus*. The last-named species actually appears not to breed on the Peruvian coast, and it is very doubtful if any gull adds significantly to any of the deposits. *Rynchops nigra* has become extremely rare. Tschudi does not mention *Pelecanoides garnotii* and considered (1846a) that *P. bougainvillei* was commonest in the southern part of the coast. His remarks apparently refer mainly to the Chincha Islands and to the southern guaneras now in Chile.

The next notes are contained in the work referred to as Rivero (1852). In this work there are some formal ornithological remarks, attributed to Raimondi, a general paragraph on the destructiveness of the natives of the coast who took vast numbers of sea birds and their eggs for food, and a specific statement by Carter, about the birds taken from El Pelado in the Huaura group.

The formal notes were written prior to Raimondi's visit to the Chincha Islands and within two years of his coming to Peru. They merely give an indication of the general habits of the species listed, namely, the piquero, nesting in large companies, referred to *Sula* without specific designation, the pelican, the skimmer, *Rhynchops nigra* Linnaeus, the cormorant, *Phalacrocorax gaimardi*, gulls referred to *Larus* without specific designation, and *Pelecanoides garnotii* which is regarded, as in Raimondi's later writings, as the most important species. The word guanay is not mentioned as the vernacular name of any of these birds. The general account of the guano deposits of the Chinchas in this work, evidently based on Rivero's visit in 1845, speaks of the thousands of birds that produce the wealth of the islands nesting in excavations in the guano. This clearly refers to *Pelecanoides garnotii*. It is perhaps noteworthy that none of Tschudi's species (*Sula variegata*, *Larus modestus*, *Phalacrocorax albigula* = *bougainvillei*) is mentioned by name, though they appear in the next of Raimondi's publications. Raimondi presumably did not have access to Tschudi's works at the time the notes were written; the testimony as to the abundance of piqueros is thus probably independent of Tschudi. It must, however, be remembered that in 1852 Raimondi had

evidently not visited the Chincha Islands.

The writer of the general notes on destruction of birds speaks of canoes loaded with piqueros, huanaes, potoyuncos, and eggs as a common sight in the harbors of the Peruvian coast, and Carter, writing of El Pelado, an islet in the Huaura group, says specifically that 24,000 piqueros and huanaes and 12,000 eggs were taken annually from this islet. These remarks indicate clearly that the guanay was a well-known and exceedingly abundant bird on the central part of the Peruvian coast about 1850.

For the year 1853 there is abundant evidence on the bird fauna of the Chincha Islands, which were visited by the Official Commission appointed to measure the guano, of which commission Raimondi was a member, and also by George Washington Peck (1854), an admirable observer whose lack of scientific training was more than balanced by a sensitive and lively intelligence.

Raimondi spent 40 days on the islands in August and September. He gives the following notes on the birds observed.

Pelecanus o. thagus, a resident species, produces very little guano as it lives chiefly on the reefs surrounding the islands, though there was a colony in the northern part of North Chincha.

Phalacrocorax gaimardi and *P. bougainvillei* (sub *albigula*), termed by Raimondi "Pato de mar" and "Cuervo de mar," respectively, are said to be unimportant as they breed on the cliffs, and most of their excrement falls into the sea. The term "Cuervo de mar" is given by Murphy as the commonest vernacular name for *P. olivaceus*, a species that Raimondi (Murphy, 1936, p. 291), like Tschudi, presumably misidentified as a snake bird (*Anhinga*). Raimondi regarded this bird as a rare visitor to the Chincha Islands, so that, although he does not mention the guanay as such, his two cormorants are evidently the two now living on the island.

Sula variegata is said to produce more guano than either the pelican or the cormorants, because it occupies the interiors of the islands. Specifically Raimondi mentions a colony in the western part of North Chincha Island.

Rynchops nigra is described as a rare

visitor of no great importance. *Larus modes-tus*, though occupying the eastern part of North Chincha, is said not to be important enough to add significantly to the deposits. It is, moreover, improbable that this gull ever bred on the islands, and gulls in general do not produce true guano deposits, the nests being built of algae, etc., and much of the excrement evidently deposited away from the breeding site.

Larosterna inca, at the time of Raimondi's visit, appears to have visited the islands seasonally. At the end of August there were a few; on September 12 a great number had appeared on the north island, and on September 15 a vast population covered the south and central islands as well as a great part of the north island. While the birds were on the islands in such vast numbers, it may be supposed that they were effective contributors to the guano.

Spheniscus humboldti was evidently far more abundant than it is today. The main colony appears to have been on the south island; Raimondi supposed that they were driven from the other islands by shipping and other forms of human interference. He states that the penguins dig burrows in the guano; it is probable from Peck's account that they also occupied caves on the other two islands. At the time of Raimondi's visit the birds were breeding.

Pelecanoides garnotii was regarded by Raimondi as the most important guano bird. It had riddled the surface of the guano of the southeastern part of the north island and the whole of the other two islands with its burrows and was evidently present in vast numbers.

Raimondi points out that fossil eggs found in the guano tended to fall into two groups, one the size of the egg of a partridge, corresponding to *Pelecanoides garnotii* (pl. 8, fig. 3) for which egg Murphy (1936) gives the dimensions as 46–48.5 mm. by 33–37 mm., and the other the size of the egg of a turkey, corresponding to *Spheniscus humboldti* (pl. 8, fig. 2) for which egg Murphy gives the dimensions as 69–74 mm. by 51–57 mm. A third intermediate class was said to exist but to be very rare. The small *Pelecanoides* eggs were the commonest. Raimondi also says he found a humerus and tibia corresponding to

those of *Pelecanoides* at a great depth in the guano. These finds led him to suppose that *Pelecanoides* and *Spheniscus* had in the past, as in 1853, been the most important guano birds. The evidence from two fossil bones is hardly conclusive, and the evidence from the eggs could be most reasonably interpreted as showing that deserted eggs of burrowing species are more likely to be fossilized than those of surface breeding species. The eggs of other guano birds would doubtless be eaten by gulls if left by the parents, rather than be gradually converted to oxammite and taylorite.

George Washington Peck (1854) visited the Chincha Islands in October and November, 1853, just after Raimondi and the Official Commission. It is possible from Peck's account to corroborate much of the general information about the bird population of the Chincha Islands given by Raimondi. The commonest bird at the time of his visit evidently was *Larosterna inca*. Peck describes having seen the surface of the guano blue with them for a space of more than 10 acres, while the precipitous cliffs were alive with the birds. Though he terms them "Poto-Huenca," the description ("like blue pigeons, but more lightly formed, and with fire-red bills. On each side of the head is a single narrow feather reaching half-way down their necks") cannot possibly refer to any other species. Peck believed that these birds nested on the cliffs. He also states that a white species of bird was very numerous. "They are a little larger than the blue, and snow white"; the "white keep by themselves in the midst of the blue, like the staff of a great army, or like a division of allies in different uniforms on the sloping hills of guano." They were also said to abound on the cliffs. Some of Peck's companions appear to have amused themselves by the indiscriminate shooting of birds, so that he presumably had a chance to examine the white species in the hand. Though a number of piqueros sitting facing the observer would give the impression of largely white birds, it is curious that if Peck had seen this species at close range, he should not have amplified his description. It is, however, hardly possible to assign the white bird to anything but *Sula variegata*. The third abundant bird was evidently *Peleca-*

noides garnotii, "beautiful little black-winged, white-breasted birds, not larger than squab pigeons, who have their nests in holes in the guano, about a foot beneath the surface and three feet within. The guano is everywhere perforated and honeycombed with these holes." Peck observed penguins, but though they were clearly more abundant than today, he writes of them in paragraphs dealing with the cliffs and caves, and it seems probable that they were mainly associated with the latter, in spite of the colony on the south island mentioned by Raimondi. Pelicans were evidently extremely abundant, around both the Chincha Islands and the Ballestas Islands. It is not clear where they bred, and it seems likely that as Raimondi indicates them mainly on outlying stacks, they were less easily noted by Peck when at rest than when flying over the sea. One remark of Peck's possibly suggests that Raimondi had underestimated their significance. Peck was told that it was illegal to kill pelicans, on account of their value as guano birds. The decree prohibiting destruction of birds on the islands (quoted in Great Britain, Parliamentary Sessional Papers, 1852), however, simply refers to birds, chicks, and eggs without designation of species. It is possible that the interpretation of the decree in favor of the pelican suggests that this species was generally believed to be of prime importance. The only birds that can be identified as cormorants were "red billed and black ducks, or birds resembling ducks" also referred to as divers. Peck does not mention these birds at the Chincha Islands, but says of the Ballestas Islands that "every rock and cliff around the islands holds a populous colony." He specifically refers to the birds as breeding in a cave. The description is hardly an accurate one for any of the species likely to be involved, but the coloration of the bill and the nesting habits indicate *Phalacrocorax gaimardi* Lesson in which the bill is "horn-yellow blending into orange toward the base; gular sac orange-red" (Murphy, 1936, in which work cf. pl. opp. p. 1144).

Kinahan's bird notes, for the same time in the summer and autumn of 1855, are harder to interpret. He writes, "Sea birds are very numerous: among other species pelicans, cormorants, terns, prions, mutton-birds, a little

land-bird like a grackle; a long red-billed wader, like an oyster-opener in its habits and note; Mother Carey's, Cape pigeons, gannets, divers, and on one occasion an albatross; penguins were formerly common, but are now very rare immediately about the island, though said to be still abundant at the Ballestas." It is obviously impossible to base any statements about such petrels or shearwaters as may have been observed on this list. The wader is presumably *Haematopus ater* Vieillot and Oudart, recorded by Murphy as occurring more commonly than *H. ostralegus pitanay* Murphy on the guano islands. The mutton bird is identified as *Puffinuria urinatrix* and a description is given, leaving no doubt that this bird was *Pelecanoides garnotii*, which Kinahan found breeding in burrows "everywhere on the surface of the guano, on the summits and one side of the hill" on the south island. The account given by Kinahan is unhappily vague, as he seems to have known something of ornithology and to have neglected his opportunities. In so far as it goes it suggests conditions not greatly different from 1853, though possibly indicating a reduction in the numbers of penguins.

In 1862, when Blumé and Rucker surveyed the island, birds are said to have been decreasing owing to human interference, but still to have been numerous enough to suggest to the observer their former abundance. The only species indicated is the burrowing bird on the south island which formed the sole food supply for the laborers there (Anon., 1863). This may refer to both the potoyunco and the penguin.

After 1862, little is known of the bird population of the Chincha Islands until the opening of the twentieth century, except that by 1869 birds had become extremely scarce, as has already been indicated (p. 51).

There is, however, a curious footnote to Raimondi's (1876, p. 312) reprint of the account of Juan and de Ulloa, appended to the word *Guanaes*, which he says are marine birds belonging to the genus *Sula*. He continues that such are not the only guano birds, the chief ones being species of *Sterna* (i.e., *Larosterna inca*), *Puffinuria* (= *Pelecanoides*), and *Spheniscus*, "pero en menor escala algunas especies de Pelícanas, Carbo y Larus." It is clear from these remarks that Raimondi

did not know what a guanay was. Moreover, Markham (1880) a little later speaks of the "guano bird" as *Sula variegata*.

In 1906 information again becomes available from Coker's (1919) excellent discussion. He found the guanay in vast numbers, over 20 acres of birds occupying South Chinchá Island and other smaller flocks on other islands. Next in importance was the pelican, though the breeding colonies were confined to two islets off North Chinchá. Evidence of abandoned pelican colonies was found on other islands of the Chinchá and Ballestas groups as well as on San Gallán and the Santa Rosa Islands. It appears that in the latter place the whole of the brood had been destroyed by a guano extractor who found the young birds to be in the way. *Sula variegata* was considered the third most important bird by Coker. The main change since Coker's day has been a further decline in the number of pelicans and an increase in the number of both *Sula variegata* and *Phalacrocorax bougainvillei*, as has already been indicated. It seems probable that in quite recent years the decline in the number of pelicans has been arrested.

Summarizing the evidence derived from the Chinchá Islands, it appears that prior to about 1825 the guanay was the most important guano bird, though the other species were doubtless present. Sometime between 1825 and about 1850 the guanay declined in numbers, though it was evidently present in large populations on other islands without permanent guano caps, such as El Pelado. With its decline there was probably an increase in numbers of other species, as the islands seem to have been occupied to saturation in 1853. At this time the potoyunco became the most numerous species, though not necessarily the best guano producer as Raimondi supposed. *Sula variegata* must have remained important throughout all this period, as is evident from both Tschudi's and Raimondi's remarks. While the existence of depressions in the population of the guanay is well known, the middle nineteenth century minimum in its numbers on the guano islands seems much more marked and far more persistent than the cyclical minima discussed previously. It is, moreover, clearly not entirely a question of absolute decline in numbers but of rela-

tively complete desertion of the islands with guano caps at a time when they carried immense bird populations, while other islets without such caps possessed large guanay populations.

It may also be noted that the period between the excessive rains of 1845 and those of 1864 is the longest interval in Eguigúren's record between years of extraordinarily great precipitation, a fact which strongly suggests that no markedly abnormal years occurred for some time after the catastrophe recorded by Cookson, which conceivably may be referable to 1845. It is hardly possible to avoid the conclusion that in the middle nineteenth century competition for breeding space on the undisturbed guano caps on such islands as the Ballestas and South Chinchá operated against the guanay and in favor of the other birds and that not until the guano was removed and the other species driven away or reduced in numbers could the guanay return in the vast numbers now present, and also implied prior to 1825 by Juan and de Ulloa and by Stevenson.

There is little information available on the changes in the bird populations of the other islands. Peck's account indicates that the Ballestas Islands probably had an ornithological history comparable to that of the Chinchás. The notes already given (p. 27) suggest that while the same may be true of Isla Colorada off the south end of Lobos de Tierra, the changes on the other northern islands have been less dramatic than on the Chinchás.

On Lobos de Afuera, Carter noted very numerous birds, piqueros dominating. Duffield, apparently writing of the same island, speaks of the guano producing bird as the heguiro, which is probably a misreading of piquero. He says that it has blue legs, so that *Sula nebouxi* is certainly implied. Murphy states that today *S. variegata* is less common than *S. nebouxi* on Lobos de Tierra, and the two species are equally common on Lobos de Afuera. The name piquero in this part of the coast is, according to Murphy, used for *S. nebouxi* so that Duffield's remark is reasonable.

Guafíape Island certainly had a guanay colony in the middle of the nineteenth century. In 1870, a cargo of guano was shipped

on the "Elliot Richie" from Guafape, bound for Baltimore. The vessel was disabled off Cape Hatteras and put into Charleston, where the cargo was sold (Shepard, 1870b). A number of mummified birds was present in the guano; some of these were forwarded by Charles U. Shepard, Jr., State Inspector of Fertilizers, to the Peabody Museum, Yale University. The material was apparently sent in two lots. The first lot bears the locality Guafape and the name of F. E. Taylor and is registered as 97. This number refers in the register to a collection of fossils, mainly from the South Carolina phosphate beds, sent by Shepard in 1870. The second lot, registered as 312, is expressly stated on the label to be from the "Richie" cargo and is indicated in the register as presented by Shepard in 1872. Though a later label expresses the possibility that the two collections do not belong together, there can be little doubt that they both are of the same origin. The elder C. U. Shepard obtained a number of guano minerals from this cargo, and it has been possible to recover specimens of some of them from the debris surrounding the birds.

In the larger collection (312), there are two pinniped fragments and the remains of at least 23 birds. One large fragment of a bird with both feet, and another isolated foot (pl. 9, fig. 2), belong to *Pelecanus o. thagus*, the measurements of the middle (longest) toe, with claw, being 130 mm. and 127 mm., and the tarsus of the second specimen being 105 mm. (not measurable in the first specimen). Murphy gives:

	FEMALES	MALE
Middle toe and claw	127-132 mm.	147 mm.
Tarsus	91-101	108

The general form of the isolated foot of the mummified specimen is obviously identical with that of a modern African pelican with which it was compared.

The other 21 birds are apparently all cormorants and may be reasonably attributed to *P. bougainvillei*. The material can be divided into two series. Five specimens bear remains of feathers; the others do not. The feathered specimens are presumably more recent than the others and were doubtless living on the island shortly before the cargo was quarried. One of them (now marked no. 5), consisting

of a wing, leg, part of the side, and associated feathers (pl. 9, fig. 1), has the following measurements:

Outer toe with claw	93 mm.
Tarsus	68
Wing	282
Radio-ulna of wing	170±
Carpus and manus of wing	110

Murphy gives for the species:

Outer toe with claw	90-105 mm.
Tarsus	66-71
Wing	270-303

The feathers remaining on the bird are in agreement in their coloration with *P. bougainvillei*, the bird having had dark wings and a light ventral surface. There can be no doubt about the identity of this specimen, and the other four birds with feathers, though presenting fewer measurable parts, are in agreement with the guanay in such characters as are available. The two that have adequately preserved feet have the outer toe of lengths 93 mm. and 94 mm.; one of these has a tarsus of 70 mm. The other two (no. 9 and no. 18) have wings which, though damaged, appear to agree in their skeletal proportions with those of no. 5.

The remaining birds lack feathers. Of this series no. 1 consists of a head, neck, and wing. The radio-ulnar section of the latter measures 170 mm., as in no. 5. Two other skulls (nos. 14 and 19), agreeing with no. 1, are also present.

The other featherless birds have all permitted foot measurements. For 10 of them the limits of variation are as follows:

Outer toe and claw	82-96.5 mm.
Tarsus	61-68

For the three cormorants inhabiting the Peruvian coast Murphy gives:

	OUTER TOE AND CLAW	TARSUS
<i>P. gaimardi</i>	89-98 mm.	50-54 mm.
<i>P. bougainvillei</i>	90-105	66-71
<i>P. o. olivaceus</i>	76.5-93	50-59

It is clear that while the toe measurements are not diagnostic, the length of the tarsus precludes any species but *P. bougainvillei*, even though two of the specimens (nos. 13 and 21) are undoubtedly young, partly

grown birds. There are two other specimens in this series (nos. 4 and 3), with toe 86 mm. and 66 mm. and tarsus 52 mm. and 43 mm., which are presumably still younger guanays but which obviously cannot be more precisely identified. Five isolated feet clearly also belong to *P. bougainvillei*, but they may have been broken off the larger mummified fragments already enumerated. If it is assumed that the skulls represent different specimens from the body fragments, which seems probable, the series registered as 312 therefore consists of:

- 2 *Pelecanus o. thagus* without feathers
- 14 *Phalacrocorax bougainvillei* without feathers
- 2 Probably *Phalacrocorax bougainvillei*, large nestlings without feathers
- 5 *Phalacrocorax bougainvillei* with feathers

The material in the lot registered 97 is less illuminating; it consists of a skull (no. 104) very like those of the other series and four mummies of similar appearance. Only two are measurable:

	No. 101	No. 102
Outer toe and claw	82 mm.	80 mm.
Radio-ulnar of wing	115	—

The four mummies of this series are in general comparable to no. 4 of the other series and are all probably young guanays.

It would appear therefore that taken as a whole the collection represents two pelicans, 26 guanays, and no bird of any other species. *Sula* and *Pelecanoides* are definitely absent. The absence of the former probably merely indicates that the guano came from part of the island inhabited by guanays rather than piqueros. The absence of *Pelecanoides*, however, would seem to imply that at the time the guano was formed this bird cannot have been present burrowing all over its surface and more abundant than the guanay, as on the Chinchas in 1853.

In addition to the data presented in this section reference may be made to the discussion already given (p. 20) of apparent changes in the breeding habits of the piquero, and to the increase in numbers of guanays and the decrease in numbers of pelicans during the present century. The record of Forbes (1914a) of the breeding of *Sula nebouxii* at Guafñape early in this century,

south of its present range, may also be noted in passing.

THE CHRONOLOGY OF THE PERUVIAN GUANO DEPOSITS

From the time of von Humboldt (1806), who erroneously considered that but a few lines thickness of guano had been produced in three centuries, the problem of the chronology of the deposits on the Chinchas and other Peruvian islands has received the consideration of naturalists. Many rather speculative estimates have been given for the time taken to produce the deposits, and some authors have felt uncomfortable about the short span apparently indicated by their calculations. This discomfort is largely due to the *a priori* contention that since the orography, and so presumably the oceanic circulation, of the Peruvian coast is of Tertiary origin, and since most of the guano birds are endemic to the region of the Peru coastal current and so are probably of fair antiquity as taxonomic entities, the product of the interaction of birds and hydrography must also go back into the historically, if not geologically, remote past. This is essentially the point of view taken by Murphy (1936) who tended to regard the problem of guano chronology as insoluble and largely meaningless. Murphy compares the guano caps as developed on the Chincha Islands to glacial caps and supposes that they represented a steady state. Each cap, while it gained constantly from new deposition of guano, lost material by "centrifugal pressure, wind erosion, and the constant treading, scratching and wing-beating of numberless birds." Murphy thus supposes that mechanical processes acting on the surface of the deposits as they existed in the early nineteenth century removed as much material as was contributed by the birds, so that the whole cap was in a steady state. This would imply that the lower layers could be of any degree of antiquity. He suggests that the deeper layers of the Chincha deposits may well be as old as the ancient elevated guano on the Mejillones Peninsula and believes that the massive fossilized appearance of birds' eggs taken from Chincha guano supports this contention of an age of thousands or tens of thousands of years. Girardin and Bidard (1844) long ago had

expressed the opinion that the Peruvian guano was to be regarded as an ancient or fossil excrement.¹ Raimondi had effectively disposed of this contention on the ground that pottery and slightly curved pieces of wood probably used as picks had been found at a fair depth in the Chincha Islands deposits. This argument is still valid and apparently conclusive. Since, as is indicated below and as is discussed in greater detail in a separate work by Kubler (1948), artifacts have been discovered in both the Chincha and Macabí deposits at depths up to 18 meters below the surface, at least 36% of the observed maximum depth has been deposited within the span of human settlement in Peru. There can therefore be no question of the establishment of a steady state until comparatively recent times. It is reasonably certain that at the time of Raimondi's visit much guano was being lost as the result of burrowing birds nesting in the surface layers. The detailed consideration of the stratigraphic notes given by Peck, however, indicates that in 1853 the conditions observed must have differed from those of earlier times. It is necessary, therefore, before proceeding to the chronological evidence, to recapitulate and integrate the material already presented on changes of the bird populations, and on the nature of the surface layer observed in the 1850's. In considering these matters one must keep in mind the following conclusions, already presented.

1. Both *Phalacrocorax bougainvillei* and *Sula variegata* occurred throughout the guano coast during the eighteenth and early nineteenth centuries, as they do today.

2. The guano caps on the Chincha Islands, on the Ballestas Islands, and at least on Isla Colorada of the Lobos de Tierra group supported a burrowing avifauna in their virgin condition in the 1840's and 1850's.

3. The guano at the surface of the Macabí and Guañape Islands was lower in nitrogen than was the main mass.

4. The stratification of the guano caps on

the Chincha Islands was essentially horizontal, and the loose surface material containing *Pelecanoides* burrows followed the contour of the slope of the cap, so that there appeared to be an angular unconformity between this surface material and the horizontally stratified main mass.

It is impossible to understand how a regularly stratified deposit could have been produced if potoyuncos had always occupied the islands in the numbers observed by Raimondi. Moreover, Peck's observations just summarized as conclusion 4 above and his finding that the stratification might be equivalent on either side of a depression are explicable only on the hypothesis that the guano caps in 1853 had lost surface material. Part of this loss may have been due to local exploitation in pre-Columbian and Colonial times, but since this exploitation was probably confined to the most accessible parts of the cap and was on a small scale (p. 43) and since the loose surface guano, full of burrows, extended over the whole of the caps, it is reasonably certain that an agent more general than local removal at the points nearest the landing places was in operation. Since the guanay and piquero were known throughout the guano coast prior to 1853, it is most reasonable to suppose that the main mass of stratified guano was produced by these birds, the chief agents of guano formation today. At some time prior to Raimondi's visit the guanay population declined, and *Pelecanoides*, which must have destroyed rather than produced stratification, began to increase. The conditions at the surface of the deposit, described by Peck, can probably best be explained by the combined action of *Pelecanoides* burrowing, sea lions moving over the surface, wind, and perhaps local exploitation at the margin of the cap. It is difficult to arrive at any definite conclusion about the cause of the change that led to cessation of deposition of stratified guano and to production of loose surface guano. There is no evidence of *Pelecanoides* burrows at the Macabí Islands or the Guañape Islands, but here again the surface guano appears to have been inferior, indicating a recent change in the conditions of deposition at these islands also. As a tentative hypothesis it may be suggested that during the early nineteenth century the

¹ It is evident that many opinions of its mineral rather than animal nature were circulated in the middle of the nineteenth century (e.g., Pickett, 1848), mainly it may be supposed because Peruvian law was more favorable to discoverers of new mineral deposits than to discoverers of those deposits to which the term mineral could not be applied.

increase in coastal navigation, the persecution of the birds by man, and the introduction of avian diseases with domestic poultry (Vogt, 1942) had at some time caused abnormally great reduction in the number of surface breeding forms, possibly in conjunction with the natural events at a period of ecological depression. Rivero (1827), as has already been indicated, gives some evidence of such a general decline in the southern part of the coast. The consequent slowing of the rate of guano deposition would almost certainly have permitted the material at the surface to decompose more than it had in the past. This surface decomposition may well have expanded the area available for the burrowing forms on the Chinchas and Baldestas Islands, though at Guañape it appears that in spite of increased surface decomposition guanays were still the chief birds down to 1870. This explanation would be in accord with the curious fact pointed out by Vogt, that Darwin, who was on this coast in 1835, was never sufficiently struck by the great flocks of feeding guanays and other birds to record their existence. Vogt's belief that the date of Darwin's visit corresponded to an ordinary catastrophic year can hardly be considered valid in the light of Eguigüren's rainfall record, though 1832 had what is termed good rainfall, which is a rather rare occurrence. Vogt's similar statement about Raimondi's visit repeats a slip in Coker's work, for Raimondi visited the Chinchas in 1853, not 1855.

It is, however, very probable that the loss of guano by deflation, implied by Peck's observations, had not occurred merely between 1825 and 1853, but also on previous occasions during Colonial times. Professor Kubler points out to me that a petition exists relative to the translation of the site of Pisco after the earthquake in 1688, in which it is stated that the old site of the town and one of the proposed new sites at Concordia close by were liable to receive so much guano dust when the paraca was blowing that the inhabitants were forced to remain indoors. This is said to have occurred most strikingly in August, September, and October (Urteaga and Angulo, 1940, p. 171).

While the presence of artifacts at considerable depths excludes the possibility of the

existence of a steady state of deposition and loss since remote antiquity, the foregoing discussion indicates that any evidence as to the rate of guano deposition in the centuries immediately prior to the removal of the material is likely to lead to too low results. Bearing this provision in mind the three main approaches to chronology, namely, modern rates of deposition, stratification, and archaeology, may now be considered.

ESTIMATES FROM MODERN RATES OF DEPOSITION

Peacock (1842), assuming a daily production of 4 ounces of guano per bird, pointed out that after 2500 years a large population (1,020,000 birds was assumed apparently) would produce about 115,000,000 tons. This is slightly in excess of the quantity that he believed to be present on the Chincha Islands. Rivero (1852) rather naively assumed that accumulation had been proceeding since the Deluge, which he placed, somewhat unorthodoxly, at about 6000 years prior to writing. He took the mean production of guano as 1 ounce per bird per day, probably following a personal communication from his friend Tschudi and, from his own estimate of 18,000,000 tons of guano on the Chincha Islands, he computes that a mean population of 274,000 birds would be needed to produce the deposit, a number correctly regarded as very moderate. Both Peacock's and Rivero's computations today may seem quite inadequate in their free use of invalid assumptions, but both are clearly correct in indicating an order of magnitude of but a few thousand years as necessary for the accumulation of the deposits.

Tschudi (1851), taking the bird population of the island of Iquique as half a million, supposed from his observations on *Sula variegata* that a layer 4 lines (i.e., about 8 mm.) thick would be deposited annually. The 30 feet of guano that had existed on the islands would take about 1100 years to accumulate at the postulated rate, again a very moderate length of time.

Modern writers have evidently been more skeptical and have refrained from further calculations, except for Coker who points out that at the rate of deposition observed by him, four centuries would be needed to de-

posit 100 feet, which he supposed to be the maximum thickness of the old deposits on the Chinchá Islands. He was mainly struck by the enormous quantity lost during past ages.

When any calculations of this sort are made, it is obvious that only the maximum depths of the deposits should be considered. All parts of the deposit of lesser depth are *a priori* likely to have suffered more loss of material or to have been produced by less continuous occupation by birds than in the case of the deepest part.

The rate of accumulation of modern guano has been variously given. Coker (1919) noted on South Chinchá an annual deposition of 11.1 cm., and on one of the small islands of the Lobos group a deposition of just under 10 cm. per year. Murphy (1925), however, observed on Central Chinchá 3 to 4 inches, i.e., 7.6 to 10.3 cm. in two and a half years or three breeding seasons, corresponding to about 3 cm. per year. The mean of these three determinations would be about 8 cm. per year. Though the data on which such an estimate is made are meager, the value is confirmed by Vogt¹ who apparently found the annual deposition to be 96 kilos per m². This figure, using the density of 1.223 implied by Coker, corresponds to 7.8 cm. of guano per annum. With the more probable density of 0.9 (p. 41) the thickness of the annual deposit would be 10.6 cm.

If 8 cm. per annum be taken as a reasonable estimate of the rate of modern accretion, the times taken to produce the maximum observed depths can be calculated as follows:

	YEARS TO PRODUCE	METERS	VARAS
North Chinchá Island	529	42.3	50
Central Chinchá Island	593	47.4	56
South Chinchá Island	551	44.1	52

These figures, although slightly greater than Coker's, imply that deposition began about 1300 A.D. This date is entirely unacceptable archaeologically.

¹ Vogt's calculations actually appear to contain a misprint. Presumably his statement that the total guano on 10 squares of area 100 m² amounted to 19,293.1 kilos in two years, should read the mean per square of area 100 m². Otherwise each bird produces but 1.59 kilos per year or a layer about 8 mm. thick, which seems impossibly low.

ESTIMATES FROM THICKNESS OF STRATIFICATION

The only published estimates made by observers in the nineteenth century are those of Peck and of Kinahan, already discussed. Peck's observations indicate a thickness varying between a millimeter or two up to 7.5 cm. Kinahan's notes indicate 2.5 to 15 cm. Without further information it is hardly possible to obtain any useful results from these estimates. Fortunately some such information can be obtained from Captain Merriman's photograph of the working on Central Chinchá Island, where Peck's observations were also probably made. Through the kindness of Dr. Murphy the original print has been available for study. It was found best to enlarge it 11 diameters on a metallographic plate and to print on high contrast paper, so producing a considerable increase in the definition of the strata.

The critical region of the photograph (pl. 10) is the vertical section to the (observer's) right of the men with picks. It is possible to trace one stratum from this cliff face to the top of the head of the first man, and another to the ledge on which the men are standing. The divergence of the lines from the men to the critical part of the cliff face may imply changes in thickness in the deposit defined by the strata but seems mainly due to perspective. Within the section defined by the two levels (pl. 11) there appear to be 22 well-marked alternations, apparently representing a paler, harder, and a darker, softer substance.

The man standing is probably a Chinese laborer; he is not quite erect. It is therefore unlikely that the section considered represents more than 170 cm. of the guano face, though probably more than 150 cm. The mean thickness of each stratum is therefore apparently between 6.8 and 7.8 cm., in excellent agreement with the estimate of the modern rate of accretion. Since some compression has doubtless occurred the rate implied by the stratification is perhaps closer to the modern maximum of 10–11 cm. per annum than to the modern mean of about 8 cm. per annum. Strata of this general thickness appear to be present in the upper part of the cliff face, above the level of the men. Below the level of the men there are certainly some

much narrower strata. Few if any are as close as Peck's lower estimate implies. Kinnan's lower estimate is perhaps more reasonable for the narrower banding, which is, however, indistinct and confused with the grain of the original printing paper, so that no certain statement can be made.

There can be little or no doubt that this stratification is annual; no mechanism other than changes in the guano deposition during the breeding cycle can reasonably account for it, and the fact that the estimate derived above fits with the modern rate of production increases the probability that such an interpretation is correct. The stratification at least permits us to conclude that a very considerable part of the deposit on Central Chincha was built up at about the same rate as that of modern guano accumulation. Any very remote date for the initiation of guano deposition is excluded by the study of the photographs alone, for to produce a deposit the bottom of which was 7000 years old would be approximately equivalent to regarding 90% of the total thickness as having stratifications of mean thickness of 2 cm. (or one-quarter of that observed in the critical section), and in addition 10% of the total thickness as having stratification of mean thickness of 1 mm., corresponding to Peck's pasteboard. It is hardly necessary to point out that the photograph gives no evidence at all of such a condition or any equivalent distribution of thicknesses.

ESTIMATES FROM ARCHAEOLOGICAL EVIDENCE

Raimondi pointed out, as has already been indicated, that the presence of artifacts at a fair depth rules out any immense antiquity for the deposits containing them. Apart from a brief paper by Gonzalez de la Rosa (1908), in which stratigraphic considerations are hardly entertained, no attempt has hitherto been made to assemble the considerable but scattered material on guano archaeology. In relation to the present study Prof. George A. Kubler of the Department of the History of Art of Yale University has undertaken to reinvestigate the whole matter. His detailed conclusions are presented in another paper (Kubler, 1948).

A Colonial heraldic slab was discovered in

1846 on the Chincha Islands, under 18 feet of guano. This object was sent to London and was described in the *Illustrated Times*, London (Bollaert, 1859). It was destined for the British Museum but was apparently never accessioned, and its subsequent fate is unknown. The arms on this slab have so far not been identified. There is, however, some reason to think that they are those of a municipality or other administrative entity rather than of an individual. Stylistically the slab appears to date from the latter part of the sixteenth century. A date in the seventh decade of that century would be reasonable¹ and would coincide with the incorporation of the islands into the Crown domain in 1564. It would therefore appear that 5.5 meters of guano had accumulated over the slab in about 290 years, i.e., at a rate of about 1.9 cm. per year.

A group of five objects, figured by Hutchinson (1873), was found on North Chincha Island at a depth of 62 feet, or 18.9 meters. This seems to be the greatest depth at which any artifacts are recorded. The group is rather heterogenous; one object, a stone figure pierced with a hole, has no parallels in Peru. Three of the other objects are, without better illustration, indeterminate. The fifth object, a ceramic representing a man with a rope around his neck, the so-called captive motif, can be referred to the Mochica period of Peruvian archaeology. A number of Mochica finds have also been made at Macabí Island, at depths in the guano of up to 18.3 meters. It would therefore appear that both at Macabí and North Chincha between one-half and one-third of the depth of the guano accumulated since Mochica times.

SYNTHESIS OF EVIDENCE ON CHRONOLOGY

If the modern rate of deposition were used to determine the date of the deepest Mochica finds, the result would be about 1600 A.D., which is obviously absurd for a relatively early pre-Columbian culture. If the rate derived from the deposit on the heraldic slab be used, the Mochica object would be dated

¹ Mr. Albert van der Put, formerly Librarian of the Victoria and Albert Museum, South Kensington, arrived at such a date independently of Professor Kubler. Mr. Van der Put believes, however, that the arms are private and not municipal.

at 887 A.D., which is not out of harmony with archaeological probabilities. Such a procedure would place the initiation of deposition as early in the fourth century B.C. This, however, is inconsistent with the conclusion from the stratification that a large part of the deposit certainly did accumulate at the modern rate of about 8 cm. per annum.

It has already been pointed out that there is independent evidence from Peck's observations that the surface layers were not being deposited in the same way as the earlier layers and that considerable if intermittent loss was taking place immediately prior to exploitation and possibly for some time previously. This last conclusion is confirmed by the Pisco document recording extensive deflation in the seventeenth century. The rate of deposition over the Colonial slab would therefore be expected to be abnormally low. If prior to the sixteenth century the deposition rate was normal we could regard the first 5.5 meters over the Mochica finds as representing 290 years and the lower 13.4 meters as taking, at a rate of 8 cm. per year, 169 years to deposit. This dates the Mochica find at 1400 A.D., which is certainly too late. In the absence of information as to when the rate of deposition began to decline we obviously cannot do better than to indicate 887 A.D. as the earliest date or Hutchinson's deepest find. The corresponding date for the initiation of deposition, early in the fourth century B.C., cannot, however, be considered unequivocally as the earliest possible date because of Peck's remarks about very thin strata and the presence of some such strata at least in the lower part of the Merriman photograph. In default of information as to their number, it is impossible to arrive at a precise dating of the beginning of accumulation. It at least seems unlikely that the mean distance between strata throughout the deposit was less than 1.9 cm., or about one-quarter of the observed distance in the critical part of the photograph. It is therefore not at all improbable that the Chincha Islands began to acquire their guano caps in the middle of the first millennium B.C. Earlier dates become progressively more improbable as they recede in time, but somewhat later dates are by no means excluded and are in fact quite reasonable on the basis of the available evidence.

CLIMATOLOGICAL INTERPRETATION OF THE CHRONOLOGICAL CONCLUSIONS

In a succeeding section the buried or fossil guano of the Chilean coast will be discussed (p. 109). It is desirable to point out here that Rivero (1852) fully realized that there was a considerable difference in age between the Chincha deposits and the buried material found farther to the south. To Rivero it appeared possible that some of the latter deposits were antediluvian in the strict Biblical meaning of the word. This difference in age is a matter of considerable importance, because it is clear that at an earlier period the greater part of the deposition occurred on what is now the Chilean coast northward to Independencia Bay in Peru, while at the present time the greatest deposition occurs on the central Peruvian coast from Pisco Bay to Lobos de Tierra. The major factor that has led to a decline in production on the Chilean coast is probably reduction in the number of islands, owing to a change in the relative sea level. There is, however, no reason to suppose that because great bird colonies were formerly present on the Chilean coast they must have been necessarily absent from Peru. If the Peruvian coast had been ecologically suitable, deposition of guano would have occurred contemporaneously with the deposition in Chile that produced the great fossil deposits of Pabillón de Pica, Punta de Lobos, and Huanillos. The only possible conclusion is that the Peruvian coast became suitable for the accumulation of guano but a relatively short time ago, of the order of 2000 or 3000 years, though guano deposition had previously been possible south of Independencia Bay. The only reasonable explanation of such a change is that the phenomena of the abnormal years, with warm water and violent rain, formerly occurred so much more frequently that permanent colonization and deposition could not take place. It is in fact necessary to suppose that the conditions now met with north of the Lobos Islands formerly extended as far south as the Chinchas. Such a change would correspond to a displacement of the thermal zonation of the eastern Pacific southward, though the displacement may have constituted a relatively temporary phase. Earlier guano deposits that had

formerly accumulated may well have been washed away by rains during such a phase. It is indeed not impossible that some of the phosphatic guano pobre recorded from the Chinchas and other islands represents the remains of such material, though it might be the first material deposited as the colonies were forming and the rainy years becoming less frequent.¹

One further point of climatological interest may be mentioned. While the narrowness and variability of the stratification in the lower part of the Merriman photograph presumably indicate some kind of fluctuation in population size and in the ecological conditions in which the populations lived, the critical region of the photograph already discussed and the region immediately above it, which together probably represent a time span of at least 50 years, show no indication of regular cycles. Not all the bands can be counted in the upper part of the region under consideration, but it is reasonably certain that if a regular seven-year cycle in guano deposition had occurred, it would be quite conspicuous, as crowding and spacing of bands can often be detected even when every band is not clearly defined. The rainfall record had already suggested that the seven-year cycle, though apparently a real phenomenon, is not of any great antiquity. It is therefore not unexpected that it should fail to appear in the single random span of long past time that can now be investigated.

THE CHEMISTRY OF NITROGENOUS GUANO

ANALYSES OF FRESH EXCREMENT

No really adequate analyses of the freshly deposited droppings of any of the guano birds exist. A proximate analysis of the excrement of captive specimens of *Pelecanus occidentalis thagus* was made for Coker. This material was apparently air dried but had otherwise undergone little diagenetic change. The composition was found to be as follows:

H ₂ O	9.40%
Organic matter	81.75
Total N	21.66
P ₂ O ₅	4.30 (=1.88% P)
Alkalis, etc.	3.70
Sand	0.85

The nitrogen comprises 26.5% of the organic matter, which is presumably largely, but by no means exclusively, uric acid. The ratio N:P is 11.5:1. When the analysis is calculated on a moisture-free and sand-free basis, the nitrogen content is 24.13% and the phosphorus content is 2.09%.

In order to provide a standard of reference in their studies of the organic nitrogen of commercial guanos, Popp and Marxen (1931) fed a domestic hen on fish-meal and water. They obtained the following results from the analysis of the air-dried droppings of this bird:

Total N	15.42%
NH ₃ ·N	2.76
Uric N	11.10
Purine N	1.40
Oxalate	0.09
P ₂ O ₅	15.08 (=6.59% P)

It is reasonably certain that the fish-meal used had lost nitrogen, as the N:P ratio appears impossibly low on the assumption that the food had the composition of ordinary living fishes.

Some analyses have been published purporting to show that the guano of the three major Peruvian guano birds differs in chemical composition. In view of the fact that the N:P ratio in the excreta must be practically,² if not exactly, identical with that in the food, the analyses are clearly not based on fresh, undecomposed guano, and though they may indicate that variations in nesting habit lead to variations in the amount of decomposition that the guano undergoes during drying, this is by no means certain. These analyses, which are discussed again below, remain problematical.

A parenthetic comparison is conveniently made at this point between the composition of the droppings of the uricotelic pelican and

¹ Since the above was written, Professor Kubler has examined a deposit of old guano on Central Chinchilla lying under a stratum of blown sand up to 3 meters thick. It is greatly to be hoped that it will be possible to ascertain the age of this deposit from the C¹⁴ content.

² A minute amount of ammonia might be lost from the lung epithelium, and conceivably some bacterial liberation of N₂ might occur in the gut, though this is for various reasons very improbable.

the feces of the ureotelic sea lion, *Otaria byronia*, usually incorrectly referred to *O. jubata*, which has sometimes been considered a significant contributor to the guano deposits. The urine of the sea lion, containing most of the nitrogen of its food, will mainly be lost in liquid form to the sea.

Coker (1919, I), Fallon (1899, II), and Zúñiga (1944, III) give for such feces:

	I	II	III
H ₂ O	43.96%	18.71%	25%
Organic matter	18.94	24.86	18
Total N	2.33	2.41	?3*
P ₂ O ₅	16.34	11.93	18
Alkalis, etc.	20.36	29.50	30
Sand	0.40	0.87	9
N:P	0.34	0.46	?0.38*

* The organic matter is described as "con un contenido en ázoe del 3%." This may indicate 0.54% N, which is very low, but it seems more probable that the 3% refers rather to the whole sample than to the nitrogen content of the organic matter.

The whole of the inorganic content (37.10%) of Coker's material would be accounted for by the phosphate, if present as 37.7% hydroxylapatite originating from bone. Guanos derived from seal feces are known locally on the Peruvian coast, as for instance on an islet (I, II) off Punto Loberia, Cerro Azul, and (III) an islet off Lobos de Afuera. Such guanos, analyzed for Coker, contained:

	I	II	III
H ₂ O	29.40%	23.40%	8.32%
Organic matter	17.74	18.86	48.43
Total N	2.86	3.21	7.90
P ₂ O ₅	16.80	19.88	16.89
Alkalis, etc.	27.84	29.81	25.21
Sand	8.22	8.05	1.15
N:P	0.39	0.37	1.08

While the last sample is certainly contaminated with bird droppings, the other two are obviously mainly derived from seal feces and differ so much from other Peruvian guanos, ancient or modern, that any of the ideas entertained as to the origin of much of the nitrogenous guano of Peru from pinniped excrement may be summarily dismissed.

In the pelican droppings analyzed for Coker, it may be reasonably supposed, as has already been indicated, that the greater part of the nitrogen is present as uric acid. Analogy, not merely with the droppings of Popp and Marxen's hen, but with those of

other birds, suggests that about 70% of the nitrogen will be in this form, thus accounting for 45.5 % of the material analyzed, or 55.7% of the organic matter found in such material.

Of the other constituents that have been determined in analyses of guanos collected in a more or less aged condition, guanine is presumably present in the purine fraction of the freshly deposited material. Hoppe-Seyler (1871) found none in hen or goose excreta, but records that Härter detected it in the droppings of a heron fed on animal food. Oxalic acid, which according to Elschner (1913) could not be found by Prescott in guano bird droppings, is probably not present in the freshly deposited material. Popp and Marxen, as has been indicated, found 0.09% in the droppings of the hen fed on fish-meal, but in view of the ease with which oxalate can be formed bacterially and, under certain conditions, chemically (Flaschenträger and Müller, 1938) from uric acid, allantoin, etc., it is quite likely that even this small amount was not present in the fresh excrement; the authors reporting its presence clearly regard the quantity found as negligible.

ANALYSES OF MODERN GUANOS COLLECTED IN NATURE

At the present time the guano collected in Peru is gathered after it has remained on the islands for a variable period up to three years. Analyses of modern guanos, therefore, will represent material that has had such opportunity for chemical change as is afforded by the peculiar climatic conditions of the islands. The extent of such change will vary in part with the time of exposure and in part with the variation in the climate. The northern localities are more likely to be subjected to temporary damp conditions than the southern.

During the nineteenth century, virtually all the guano collected and analyzed was of considerable age, and although on the Chincha Islands such material was not very different from that collected now from the Peruvian islands, there is no *a priori* reason to suppose that material that has on an average been lying on the islands for centuries will be identical with that which has lain for but a few years. In one locality, however, namely, Angamos Point off the Mejillones Peninsula,

TABLE 2

	Angamos			Ballestas					Lobos de Afuera
	Nesbit		Voelcker	Coker					Coker
H ₂ O	7.64%	11.33%	8.76%	20.26%	19.77%	19.95%	19.80%	18.20%	16.14%
Organic (ign. loss)	70.21	52.92	69.96	56.59	54.23	54.10	51.80	51.15	43.86
Total N	20.09	14.38	19.30	15.91	15.40	14.95	14.58	14.41	8.41
Total P ₂ O ₅	6.09	9.60	5.53	8.89	10.35	10.36	10.48	11.19	17.40
CaO*	3.12	10.07	6.54						
				13.51 ^b	—	—	—	—	13.50
Alkalis	9.37	8.99	8.27						
Sand (silica)	3.55	7.08	0.94	0.75	1.35	2.30	1.60	3.60	9.10

* Calc from phosphate, and perhaps including MgO.

^b "Alkalis, etc.," probably including alkaline earths.

now in Chile but formerly in Bolivia, the fresh guano, probably of non-breeding birds, was regularly collected during the nineteenth century. It is logical to include the available analyses of Angamos guano, which exceeds in nitrogen content all other guanos collected in nature, with those of twentieth century guanos rather than with the old deposits worked in the nineteenth century.

Proximate analyses of the relatively recent accumulations of guano forming on the Bal-

leestas Islands, where the producing birds are guanays, and on the Lobos de Afuera Islands, where the producing birds are pelicans, have been given by Coker, while Nesbit (1860) and Voelcker (1876) have given data for the material from Angamos. The more complete of these analyses are given in table 2.

Somewhat more detailed analyses of Angamos guano (Nesbit, 1860) and of modern Peruvian guano from the Santa Rosa Islands and Asia Island (Cancino, 1935) are given in

TABLE 3

	Angamos (Nesbit)	Santa Rosa Is. (Cancino)	Asia Is. (Cancino)	<i>Pelecanus</i> <i>o. thagus</i>	<i>Phalacrocorax</i> <i>bougainvillei</i> (Lavalle, 1912)	<i>Sula</i> <i>variegata</i>
H ₂ O	22.28%	20.40%	18.58%	14.57%	18.95%	5.58%
Water soluble	—	—	—	38.86	44.96	15.40
Organic (ign. loss)	56.03	50.30	42.25	—	—	—
Ash	—	—	—	27.46	36.06	72.70
Insol. (SiO ₂ , etc.)	1.47	1.78	6.90	0.39	0.47	2.40
Na ₂ O	3.51	—	—	—	—	—
K ₂ O	2.51	2.48	2.38	0.67	1.94	2.07
CaO	3.67	10.93	9.85	9.16	13.16	7.20
MgO	0.50	—	—	—	—	—
P ₂ O ₅	7.14	11.17	12.60	10.15	13.10	5.75
(Al,Fe)PO ₄	0.85	—	—	—	—	—
Cl	2.16	—	—	0.54	0.10	0.35
SO ₃	0.30	—	—	—	—	—
N total	17.41	14.64	10.81	15.54	11.76	5.46
N organic	—	9.84	6.33	12.18	8.12	2.02
N · NH ₃	—	4.73	4.38	3.22	3.50	3.30
N · NO ₃	—	0.07	0.10	0.14	0.14	0.14

TABLE 4

	Santa Rosa No. 6279	? No. 6278	Pachacamac No. 6277	? No. 6390
Moisture	17.5%	14.5%	20.0%	18.0%
Total ash	28.1	34.0	40.2	37.7
Insol. in HCl (i.e., sand)	3.4	4.4	10.3	3.2
CaO	9.6	11.6	11.9	10.5
MgO	1.1	1.4	1.3	1.1
K ₂ O	1.93	1.56	2.12	1.58
Cl	0.87	1.37	1.52	3.61
P ₂ O ₅ total	10.19	10.39	12.56	9.88
P ₂ O ₅ citrate sol.	2.90	3.90	6.90	3.40
P ₂ O ₅ citric acid sol.	9.20	9.30	11.70	8.90
Ash constituents not accounted for	1.0	3.3	0.5	7.8
N total	15.59	14.28	10.21	10.02
N·NH ₃	4.76	4.28	3.94	4.29
N·uric acid	9.10	9.18	4.77	4.80
N·purines	1.41	1.11	1.30	0.93
N·guanine	0.87	0.82	0.34	—
N·keratin	0.08	0.00	0.00	0.19
N·NO ₃	0.00	0.00	0.00	0.00
N not accounted for	0.24	-0.29	0.20	0.00
Oxalic acid	4.36	3.96	3.33	5.63
Total organic carbon	17.90	17.40	10.80	13.70
C:N	1.15	1.22	1.06	1.37
Organic carbon not in oxalate, uric acid, or purines	5.69	5.56	4.72	6.24
Organic matter by combustion	45.4	46.0	32.8	36.0
Organic matter calc ^a	46.1	45.2	29.8	34.8
Organic matter as uric acid	27.30	27.54	14.31	14.40

* Uric acid+purines and keratin+oxalic acid+twice organic carbon not in these compounds.

table 3, along with three analyses supposed to demonstrate differences between the guano produced by the three chief guano birds (Lavalley, 1912). These last three sets of determinations are, as has been indicated, problematical. The *Sula variegata* guano, in which most of the ash constituents are undetermined, is particularly puzzling. There is, moreover, obviously no systematic agreement between the two sets of pelican and guanay guano analyses. In view of the lack of information as to the origin and the nature of these three samples, they are not used in any subsequent parts of the discussion.

The most important analyses are, however, those of Popp and Marxen (1931). These refer to four samples of nitrogenous Peruvian guano, without indication of provenance, designated by the ship which brought the cargo and by number. A phosphatic Peruvian guano and two Seychelles guanos, as well as a commercial preparation, were also studied by

the same authors. Popp and Marxen give a detailed account of the distribution of nitrogen in these samples. Cancino (1935) gives three fractionations of nitrogen identical with three in Popp and Marxen's paper and presumably based on the same analyses.¹ Cancino, however, knew of the localities from which the samples were derived. Thus it is possible to identify Popp and Marxen's no. 6279 imported on the "Winterhude" as Santa Rosa guano, their no. 6277 imported on the "Killoran" as Pachacamac guano. Their phosphatic Peruvian guano no. 6276, discussed below, came from Lobos de Tierra.

¹ This presumption is not supported by a statement in a letter kindly sent me by Sr. Enrique Avila of the Compañia Administradora who says that Dr. Cancino informs him that he believes all the analyses made by Popp and Marxen of guano shipped to Europe at the end of the 1920's correspond to guano harvested from North Chincha Island. If this be so, the coincidence in the analytical results is most extraordinary.

Unfortunately the origin of neither no. 6278 imported on the "Olando" nor no. 6390 imported on the "Ingo" can be identified. The latter guano is abnormal in some respects. The analyses given by Popp and Marxen are summarized in table 4.

Essentially the whole of the nitrogen is accounted for in the fractionation into ammonia, uric acid, purines, and keratin, but Popp and Marxen's analyses indicate that apparently about 10% of all their guanos consists of unidentified non-nitrogenous organic compounds other than oxalate. Rather under half of the weight of the two less decomposed guanos is organic matter and rather over half the organic matter is uric acid. No identification of purine bases other than guanine seems to have been made in Peruvian guanos, but there is an old and unsatisfactory report (Phipson, 1862a, 1863) that xanthine was present in highly decomposed material.

Gamarra Dulanto (1942) gives a fractionation of the nitrogen of an average modern guano containing 13.5% N as:

N·NH ₃	3.3%
N·uric acid	9.0
N·purines	1.0
N·keratin	0.1
N·NO ₂	0.1

but he also quotes analyses made by Crousilat that indicate a much greater purine content (p. 78).

Kinnersley, Peters, and Squires (1925) obtained a substance from guano, soluble in ether, acetone, and 50% alcohol, that fluoresces an intense blue. It is possibly urochrome and probably identical with the substance causing blue fluorescence in various animal tissues. Hoppe-Seyler (1863) recorded a gallic-acid-like substance and cholesterol. A sterol ("guanosterol") has also been detected (Noriega del Aguila, 1939) and supposedly identified as cholesterol by Krueger (1944) who obtained 4 grams from 3 pounds of guano, which therefore contains about 0.3% of the sterol. Heterauxin (3-indoleacetic acid) and perhaps xanthopterin have been detected chromatographically by Cancino (1943); both substances are very reasonable constituents in minute amounts.

In Popp and Marxen's two samples from known localities, almost the whole of the ash is accounted for. They suppose that the cit-

rate-soluble phosphate represents CaHPO₄ and the rest Ca₃P₂O₈. Some of the calcium, however, may be present as oxalate. Evidence from old guanos suggests that both soluble and insoluble oxalate was present, the insoluble presumably being calcium oxalate. Popp and Marxen concluded that their calcium contents agreed with the distribution of calcium phosphates that they postulated. Cancino, however, found that 4.15% water-soluble P₂O₅ was present in the Santa Rosa guano and 4.31 water-soluble P₂O₅ in the Asia guano analyzed by him. It seems more likely that this water-soluble phosphate is present as ammonium phosphate and that some calcium is present as oxalate. The molecular ratio CaO:P₂O₅ is of interest in the study of phosphatic guanos taken up later and has been calculated for such modern guanos as have been adequately analyzed.

Angamos	1:0.745
Santa Rosa (Popp and Marxen)	1:0.419
Santa Rosa (Cancino)	1:0.401
No. 6278 (Popp and Marxen)	1:0.353
Pachacamac (Popp and Marxen)	1:0.416
No. 6390 (Popp and Marxen)	1:0.370
Asia (Cancino)	1:0.506

The sample designated no. 6390 by Popp and Marxen differs markedly from the others in having over 20% of its ash not accounted for by the substances determined in the analysis. It is clear that part of this deficiency is due to sodium which presumably balances the rather greater amount of chloride present here than in the other samples. Mere contamination by sea salt, however, will not account for the deficiency. The sample may have contained more sulphate than the others.

DECOMPOSITION OF ORGANIC NITROGEN COMPOUNDS IN GUANO

Gamarra Dulanto (1942) observed that the nitrogen content of fresh guano kept in an uncovered capsule in the laboratory fell from 20.21% to 17.11% in 49 days. He found that the process was mainly aerobic and was prevented by the use of antiseptics. On the island of Don Martin samples collected at intervals after deposition, varying from 30 days to 308 days, showed, however, no systematic decrease in nitrogen content with time, but guano that had lain two years on the island was poorer (12.66%, 13.71% N, or on a water-

free, sand-free basis 17.38%, 18.42% N) than guano that had lain one year (15.16% N, or on a water-free, sand-free basis 19.56% N). Gamarra Dulanto's richest sample (15.76% N, or on a water-free, sand-free basis 21.06% N) had lain 222 days on Don Martin Island, while his poorest on a water-free, sand-free basis (14.81% N, or on a water-free, sand-free basis 19.00% N) was but 30 days old. He considered that the differences observed in samples from a given island may be due to differences in the composition of the food and possibly to differences in the proximity of feeding grounds used at the times of deposition of the various samples.

There is no doubt that at the present time the nitrogen contents of the material collected commercially tend to be lower on the damper islands, falling to 11% to 13% N on Lobos de Tierra in the north, and higher on the drier islands, rising to 15% to 16% N on Santa Rosa in the south. It appears that the humidity of the intermediate islands does not vary in quite regular manner down the coast, particular islands, as Asia Island, being noted (Anon., 1945b) as having a damp atmosphere. Gamarra Dulanto indicates that the nature of the wind may be important in maintaining favorably dry, or less favorable moist, conditions.

The decomposition of relatively fresh nitrogenous guanos has been studied by Copeman and Dillman (1937), using South African material. Their results, however, are presumably applicable to all nitrogenous guanos. By storing two samples from each of six specimens, so that one sample became air dry while the other remained in air saturated with water vapor for seven to 10 weeks, they found the following mean changes, nitrogen being calculated on a moisture-free basis:

	MOISTURE	TOTAL N
Original	13.84%	11.92%
Dry	8.04	11.56
Moist	23.32	10.98

The difference in total nitrogen between the original samples and those dried in air is statistically significant and is apparently due to volatilization of ammonia held in the original water content of the material. The larger loss of total nitrogen under wet condi-

tions is due primarily to two of six samples, and the mean is not statistically significantly different from that for the original samples. There has, however, here been a significant decrease in the uric acid content and a concomitant increase in ammonia. The conditions for the most rapid loss of nitrogen by volatilization, therefore, appear to be alternate exposure to wet and dry air. When the guano is in contact with liquid water, the rate of decomposition of uric acid is such that the ammonia increases from 30.8% of the total N to 85% of the total N in four days. This rapid decomposition of uric acid does not occur under sterile conditions and is certainly bacterial.

Since the decomposition of uric acid results in the production of water-soluble ammonium salts, the proportion of the nitrogen that is water soluble increases as the nitrogen decreases. This is well shown in three samples (Anon., 1945a) of different nitrogen contents from Peru:

N	SOLUBLE IN H ₂ O
16.35%	27.91%
12.46	35.87
8.26	55.56

Copeman and Dillman made no attempt to isolate products of the decomposition of uric acid, other than ammonia, but Maschhaupt (1908) had previously shown that incubation of guano at 30° to 35° C. for two months led to a fall in uric acid from 17.9% to 6.0% and a rise in oxalate from 3.4% to 9.6%. Thus for every molecule of uric acid decomposed 0.973 molecule¹ of oxalate appears.

The bacterial decomposition of uric acid can occur under both aerobic and anaerobic conditions and can be brought about by a number of different organisms. Some of these,

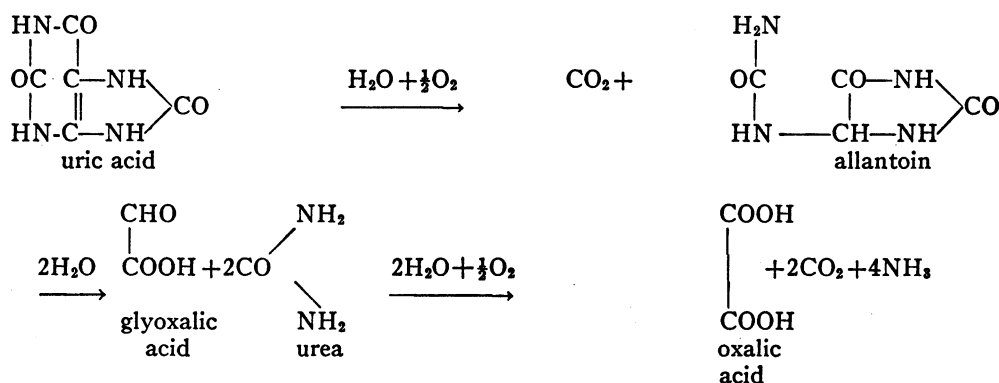
URIC N	WATER- SOLUBLE N	NH ₃ .N
4.77%	3.61%	2.85%
4.70	3.14	2.44
3.64	3.96	3.07

as *Bacillus fastidiosum* den Dooren de Jong (1929), are alleged to oxidize uric acid di-

¹ Calculated on the assumption that the oxalate is given as (COOH)₂; if it is given as (COO)₂ the figure becomes 0.995, but in either case it is reasonable to suppose a 1:1 ratio within the experimental error.

rectly to carbon dioxide and ammonia. *Corynebacterium ureafaciens* Krebs and Eggleston (1939) produces urea from a variety of compounds containing $=N-C-N=$ including uric acid and allantoin, but no studies of the non-nitrogenous metabolites appear to have been made. The obligate anaerobe *Clostridium aciduri* (Liebert) Barker and Beck (1942), which is known from soils, marine muds, and from the droppings of *Colaptes auratus*, produces ammonia, carbon dioxide, and acetic acid equally well from uric acid, guanine, and xanthine, while another anaerobe, *Streptococcus allantoicus* Barker (1943), produces from allantoin, which is easily formed from uric acid, a variety of compounds of which ammonia,

P. fluorescens Migula, *P. non-liquifaciens* Bergey *et al.* (sub *B. f. non-liquifaciens*), and an inadequately characterized soil organism designated as *Bacterium calco-aceticum* all oxidize uric acid. All four species first produce allantoin, all four apparently produce oxalic acid from allantoin, from uric acid by way of allantoin, and from calcium glycolate. The oxalate is subsequently oxidized to carbon dioxide and water. Urea is formed in the process of decomposition of uric acid or allantoin. There is no reason to suppose that glycolic acid, $CH(OH)COOH$, is produced in the cultures. Waksman, by analogy with the well-known processes of decomposition of uric acid in the Metazoa, supposes that the reaction proceeds as follows:



carbon dioxide, urea, and oxamic acid are the most important. Other workers, with less satisfactory evidence, have suggested other intermediate products of uric acid metabolism. In the decomposition of uric acid in guano the only identified product more complex than carbon dioxide or ammonia is oxalic acid. Maschhaupt's observations indicate that in the laboratory the production of oxalic acid can be practically stoichiometric on the assumption that the two linked carbon atoms are the source of the carbon of the oxalic acid. The bacterial decomposition of uric acid in which oxalic acid is produced is therefore of primary interest in relation to diagenesis in guano and may indeed be the only important type of decomposition that occurs in nature. Bacterial production of oxalic acid was noted by Bierema (1909), and was studied in detail by Liebert (1909), who found that *Pseudomonas aeruginosa* (Schroeter) Migula (sub *Bacillus pyocyaneus*),

At least under the conditions established in Maschhaupt's experiments the oxalic acid clearly does not decompose further. In the presence of three molecules of water the final products will be ammonium oxalate, $(\text{COONH}_4)_2 \cdot \text{H}_2\text{O}$, and ammonium bicarbonate, $2(\text{NH}_4)\text{HCO}_3$, which as oxammite and teschemacherite were important minerals in the old guano. Liebert concluded that as the decomposition of uric acid proceeded in his mixed cultures, and the medium became more alkaline, three species of inadequately defined bacteria appeared, but of these the metabolic characteristics are not properly described.

Nothing appears to be known about the details of the decomposition of the purine bases in guano. Ulpiani and Cingolani (1905) isolated from pigeon dung an organism that forms guanidine from guanine. If Phipson's old observations can be credited, xanthine is present in guano so decomposed as to have lost all or almost all its uric acid and appar-

ently not containing guanine either. Gamarra Dulanto (1942) gives fractionations (Crousilat analyst) of nitrogen from recent guano (I) and guano a year old (II) purporting to demonstrate the stability of the purine fraction, but the values for that fraction are so high that the analyses cannot be unreservedly accepted:

	I	II
N·NH ₃	1.58%	2.33%
N·uric acid	11.67	8.39
N·purine	5.16	5.59
N·NO ₃	0.13	0.28
	18.54	16.59

It is clear that the actual processes of decomposition cannot be adequately known until studies have been made on the bacte-

	WATER-SOLUBLE P ₂ O ₅
Total P ₂ O ₅	-0.34
Water-soluble P ₂ O ₅	
K ₂ O	
CaO	

riology of fresh guano *in situ* on the islands. In Peru it appears to be assumed (Anon., 1945b) that the organism causing nitrogen loss is *Micrococcus ureae* Cohn, the well-known species that converts urea to ammonium carbonate; it seems, however, unlikely that *M. ureae* plays any important part in the decomposition of guano. The problem is of some general interest, particularly in view of Maschhaupt's results which suggest that, in spite of the rather large number of possible paths for the destruction of uric acid, all the decomposition actually proceeds along the conventional biochemical lines followed by the three common species of *Pseudomonas* and that so long as appreciable uric acid remains no oxalate is destroyed. In addition to its general theoretical significance it is possible that an investigation of the bacteriology of guano might be of interest in relation to its storage and use as a fertilizer. It is perhaps desirable to point out that *Bacillus guano* Stapp (1920), one of a group of *Bacilli* known to attack uric and hippuric acids, was derived from soil fertilized with guano and not from pure guano as such. It is therefore not necessarily a normal inhabitant of guano in Peru.

RELATION OF NITROGEN TO PHOSPHORUS CONTENTS OF GUANO

Buzaglo (1930) has plotted the nitrogen and phosphorus contents of a large number of Peruvian guanos, finding little correlation. Copeman and Dillman computed the correlation coefficients, derived from South African guanos, which are given below. Values in parentheses are not significant to the level $P=0.01$ for which the limit of $r = \pm 0.33$. It is apparent that as decomposition occurs not merely is nitrogen lost, but potash is removed also. Copeman and Dillman say that soluble phosphate is removed with the nitrogen and potash; presumably the correlation of nitrogen and soluble phosphorus should be positive, the minus sign being a misprint.

In these works of Buzaglo, and of Cope-

	K ₂ O	CaO	N
	(-0.18)	+0.85	-0.46
	+0.44	-0.59	-0.70
		(-0.22)	+0.50
			-0.55

man and Dillman, the chemical determinations are referred to guano containing water and sand, and so cannot be used in the treatment developed below.

When the nitrogen contents of the few adequately analyzed modern Peruvian and Angamos guanos, collected in nature, are calculated on a moisture-free and sand-free basis and are related to the phosphorus contents on a like basis, it is seen (fig. 20) that an approximate linear relation between the two quantities can be derived from such relatively fresh guanos, drying and undergoing the small amount of decomposition that takes place on the islands.

If Popp and Marxen's aberrant sample no. 6390 is omitted and the phosphorus content is taken as the independent variable, the regression line, fitted by least squares, corresponds to $N = 28.18 - 1.64 P$. The point for the fresh pelican feces analyzed by Coker is found to lie close to this regression line. Moreover, if the total nitrogen content is related to the organic (ignitable) matter for such analyses as are available, the results are found to show no systematic variation with the phosphorus content. It is therefore legitimate

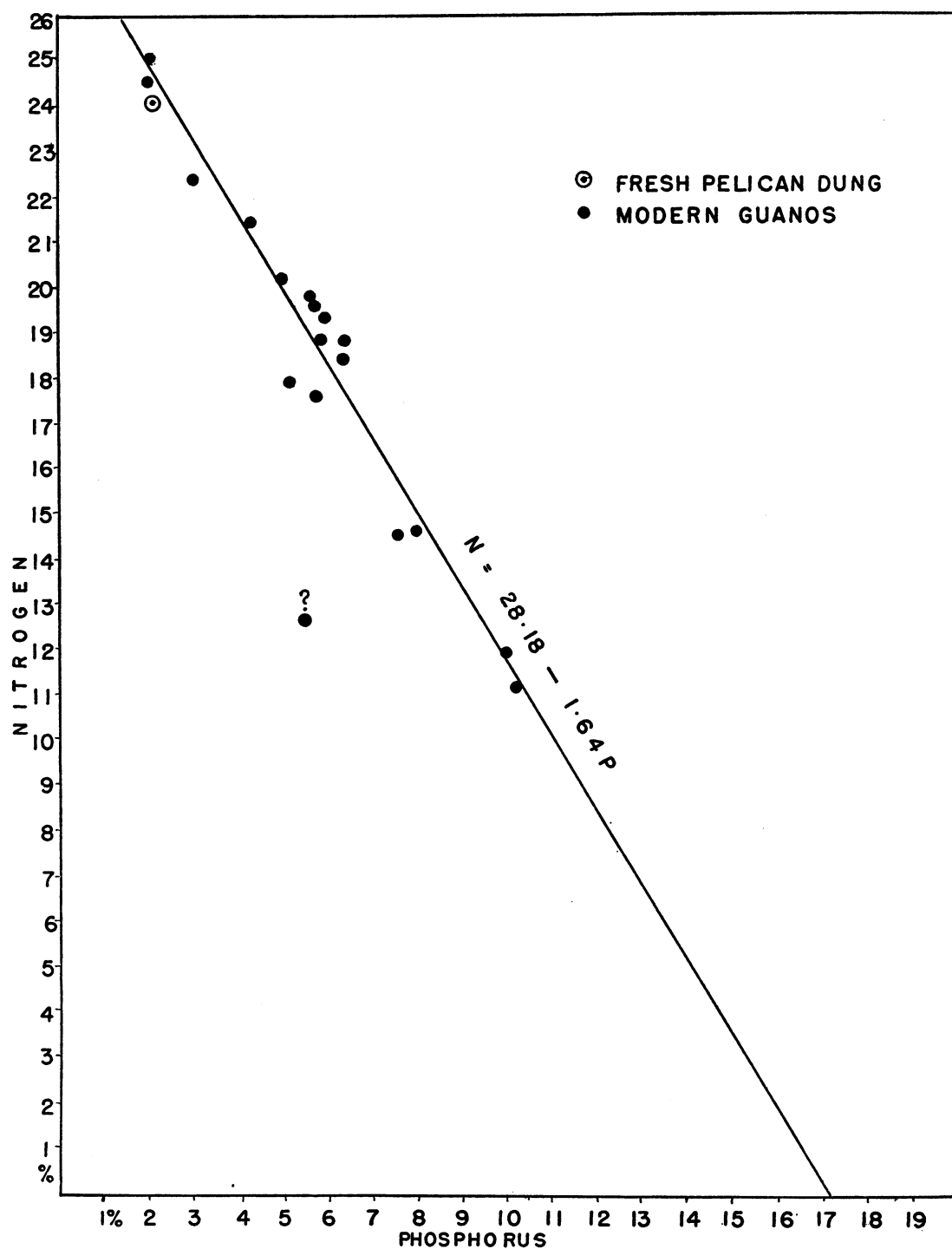


FIG. 20. Nitrogen contents of modern Peruvian guanos plotted against phosphorus contents on a sand-free, water-free basis.

to conclude that the changes that take place initially on the islands lead to a loss of some nitrogen and, as has been indicated, to a redistribution of the forms of the nitrogen that remains, but that in general the ratio of nitrogen to other volatile matter in the fractions lost and retained is about the same as the ratio in the original guano. The relation indicated by the graph merely shows that, so far as the modern deposits are concerned, variation of nitrogen content can be formally regarded as determined by the variation in the amount of less stable substances containing 28.18% N, which decompose in the presence of stable substances containing 17.17% P. The regression line, however, provides a useful standard for comparison of old guanos with the material that has merely undergone such changes as occur under modern conditions.

ANALYSES OF OLD PERUVIAN NITROGENOUS GUANOS

The chemical composition of the principal insular deposits of nitrogenous guano may be conveniently considered separately from the data available for the two most northern islands, Lobos de Tierra and Lobos de Afuera, where much nitrogen has been lost on account of occasional heavy rains.

The earliest analyses of Peruvian guano, namely, those made by Klaproth (1806) and by Fourcroy and Vauquelin (1806) on the original material obtained by von Humboldt, and the later analyses of Völckel (*in* W[öhler], 1841) and Bertels (1843) are now mainly of historic interest. They indicated that the material consisted largely of ammonium urate or uric acid, that ammonium or calcium oxalate and phosphate were important constituents, and that sulphates were significant components of the material. These analyses must have left no doubt in the mind of anyone who could have appreciated their significance of the avian origin of the material.

The three best detailed analyses of typical old Peruvian guano (see table 5) are probably those of Denham Smith's (1845) samples of ordinary guano (I and II) from an unspecified locality (probably North Chincha Island) and Karmrodt's (1861) analysis of Chincha Island guano (III). Denham Smith has also published analyses of what he termed "concrete guano" (VII and VIII) and of what he

termed "saline guano" (IX). The concrete and saline guanos are said often to have been mixed together in the same bag. Denham Smith describes his normal guano, comprising the bulk of his samples, as a damp, pulverulent substance of various tints of brown, intermixed with nodules, usually of a lighter color than the powder. Some of these nodules were soft, easily crushed by the fingers, and often present light brown silky crystals when broken; others were much harder, of a dirty white and uniform texture throughout. The light brown silky crystals were probably oxammite or natural ammonium oxalate, specimens of which have been examined in the course of the present study and which are reminiscent of Denham Smith's description.

The "concrete guano" is said to have existed as large concretions often weighing several pounds, presenting various aspects when broken; sometimes seeming merely to be the first variety in a coherent, instead of a pulverulent state; at other times appearing as a regularly stratified deposit of different shades.

The first sample analyzed (VII) is described as soft enough to shred with a knife, giving a damp, dark brown powder. The cut surface showed innumerable minute dusty white granulations. The analysis indicates a material differing from ordinary guano mainly in lacking uric acid, though rich in oxalate, and being well indurated with alkali, mainly sodium sulphate. The second concrete guano (VIII) is a quite different material; it was hard, lighter in color and drier than the other samples, and appeared to be stratified. The analysis suggests that it was about 70% monetite (CaHPO_4).

The saline guano occurred in irregularly shaped masses, termed stones by the laborers; it had a crystalline fracture, resembling a fused salt of a brown color. Denham Smith was told at the warehouses from which he obtained his sample that at least 100 tons had been picked out of the guano received for distribution. The analysis of the sample examined indicates a great quantity of chloride, which in spite of its arbitrary assignment by Denham Smith to sodium, potassium, and ammonium, may well have been nearly all present as NaCl , obviously of marine origin. It is not unlikely that the saline guano is material spoilt by sea water; it may have

TABLE 5

	I				II				III			IV	V	VI	VII				VIII				XI			
	Sol. in Cold H ₂ O	Sol. in Hot H ₂ O	Insol. in H ₂ O	Total	Sol. in Cold H ₂ O	Sol. in Hot H ₂ O	Insol. in H ₂ O	Total	Sol. in H ₂ O	Insol. in H ₂ O	Total				Sol. in Cold H ₂ O	Sol. in Boiling H ₂ O	Insol. in H ₂ O	Total	Sol. in Cold H ₂ O	Sol. in Boiling H ₂ O	Insol. in H ₂ O	Total	Sol. in Cold H ₂ O	Sol. in Boiling H ₂ O	Insol. in H ₂ O	Total
	%	%	%	%	%		%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Moisture	22.20	—	—	28.487	21.50	—	4.242	33.796	—	—	—	10.500	5.200	20.000	20.42	1.066	4.974	27.128	10.666	—	8.060	18.726	7.700	0.790	1.836	12.879
Combined water	1.500	1.331	3.456	2.636	6.174	0.740	1.140	2.060	3.61	2.29	5.90	24.860	22.400	26.999	0.668	—	—	—	0.240	1.000	2.973	4.213	2.553	—	—	—
Organic matter	—	—	2.636	2.636	—	—	2.060	2.060	—	—	—	—	—	—	—	—	0.862	0.862	—	—	—	—	—	—	—	—
Humus	—	—	—	—	—	—	—	—	—	1.60	1.60	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Fatty acids	—	—	—	—	—	—	—	—	—	1.11	1.11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Resinous matter	—	0.100	11.872	11.972	0.656	0.126	14.574	15.356	—	9.87	9.87	13.950	16.020	14.640	—	—	8.178	8.178	0	0.612	29.853	30.465	—	0.060	7.163	7.223
CaO	—	0.077	0.725	0.802	—	0.056	0.708	0.764	1.17	—	1.17	0.520	1.100	0.400	—	0.108	0.312	0.420	—	—	1.090	1.090	—	0.018	0.921	0.939
MgO	5.205	1.477	—	6.682	5.168	0.266	—	5.434	7.58	—	7.58	11.100	8.500	9.100	5.000	0.081	—	5.081	0.140	—	—	0.140	0.954	0.015	—	0.969
NH ₃	? tr.	?0.057	—	?0.06	3.370	?0.06	—	3.430	1.29	—	1.29	0.900	1.200	1.100	13.026	—	—	13.026	1.907	—	—	1.907	29.128	—	—	29.128
Na ₂ O	4.371	—	—	4.371	1.144	—	—	1.144	1.78	—	1.78	2.100	2.250	2.200	3.842	—	—	3.842	—	—	—	—	5.467	—	—	5.467
K ₂ O	3.640	—	—	3.64	2.106	—	—	2.106	2.62	—	2.62	2.060	1.960	2.000	14.414	—	—	14.414	0.680	—	—	0.680	10.654	—	—	10.654
SO ₃	4.350	0.419	10.203	14.922	5.502	0.430	10.396	16.328	2.52	8.84	11.36	12.100	19.030	12.560	7.950	0.389	3.448	11.787	0.640	0.525	38.560	39.725	2.310	0.066	7.609	9.985
P ₂ O ₅	5.030	—	1.440	6.47	6.818	—	6.032	12.850	9.88	—	9.88	4.464	3.600	3.810	6.378	—	6.164	12.542	tr.	—	—	tr.	5.563	—	—	5.563
Oxalic acid	—	16.523	—	16.523	—	2.308	—	2.308	10.59	21.14	31.63	12.000	15.500	0.900	—	—	—	—	—	—	—	—	—	—	—	—
Uric acid	1.70	—	—	1.70	2.348	—	—	2.348	2.52	—	2.52	2.966	1.240	1.500	1.813	—	—	1.813	0.866	—	—	0.866	21.241	—	—	21.241
Cl	—	—	1.560	1.56	—	—	1.648	1.648	—	0.64	0.64	1.900	2.000	1.100	—	—	0.720	0.720	—	—	2.043	2.043	—	—	0.420	0.420
Sand	—	—	—	—	—	—	—	—	—	0.55	0.55	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.150
(Al,Fe) ₂ O ₃	—	—	—	—	—	—	—	—	—	(silica)	—	>	—	—	—	—	—	—	—	—	—	—	—	—	—	—

I, II. Denham Smith (1845), normal guano.
III. Karmrodt (1861), Chincha Is.
IV. Raimondi (1878), Chincha Is.

V. Raimondi (1878), Chanavaya.
VI. Raimondi (1878), Guañape Is.

VII, VIII. Denham Smith (1845), concrete guano.
IX. Denham Smith (1845), saline guano.

come from some locality other than the Chincha Islands, though the only guanera regularly exploited at the time was North Chincha. It is evident from Tschudi's account that some work was done sporadically during the 1840's at the old southern guaneras now in Chile.

These less typical specimens having been disposed of, the normal material, exemplified by the two analyses (I, II) of Denham Smith's ordinary guano and by Karmrodt's analysis of Chincha Island guano, may be considered. It is apparent from the sums of the ammonia nitrogen and uric nitrogen that Karmrodt's analysis (III) is of a good sample, apparently containing about 10% water and almost 17% N, if the 4% magnesium ammonium phosphate of the analysis be regarded as anhydrous. Denham Smith's first sample (I) was of a fairly good guano, containing at least 11.04% N; his second sample (II) was evidently poor, with a minimum nitrogen content of but 5.24%. Comparing the two more nitrogenous samples (I and II) with the analyses of Popp and Marxen, the most noticeable difference lies in the quantity of oxalate. The impoverished specimen (III) is also rich in oxalic acid. Yet the values here given, of from 6.47% to 12.85%, are by no means the highest that have been recorded, for König (1898) gives the following data for six guanos of unspecified but presumably old Peruvian¹ origin:

Total N	8.13%	7.86%
N·NH ₃	6.53	6.30
P ₂ O ₅	14.72	14.39
K ₂ O	2.77	2.54
Total oxalic acid	18.13	19.23
Water-soluble oxalic acid	7.31	7.98
Uric N, equivalent to oxalic acid	11.28	11.96

The uric nitrogen has been calculated on the assumption that one molecule of oxalic acid is derived from one molecule of uric acid, an assumption for which evidence has already been presented. It will be observed that in

¹ High oxalate contents also characterized the old guano of southwest Africa (p. 149), but this had certainly all been exhausted before 1862 and probably by the close of the 1840's. Nearly all this African material went to British ports. Ingle (1913) quotes from "Wagner Chemical Technology 1892, p. 424," presumably an English edition of R. von Wagner's "Handbuch der

the guanos richest in oxalic acid nearly half of the ammonia that must have been produced by decomposition of the uric acid has been lost. It is also evident that in all these samples a considerable amount of the oxalate must be present as the insoluble calcium salt. König (1923), in a later edition of the same work on the chemical examination of agricultural materials, gives, according to Popp and Marxen, the following data for guanos imported as late as 1909, and therefore presumably of no great antiquity:

	OXALIC ACID
Chincha	11.92%
Guañape	8.56
Ballestas	10.40
Santa	0.30 (N = 3.29%)
Huaura	10.96
Macabí	16.82

No quantitative data for the guanine contents of old guanos exist. The compound was originally isolated by Unger (Magnus, 1844) and was first believed to be xanthine, supposedly indicating a pathological state of the guano birds. The error of this identification was pointed out by Einbrodt (1846), and the name guanine for the new compound was thereupon introduced by Unger (1846a) who found (1846b) the compound to be present in all guanos studied, though Peruvian material contained more than did African. It may be

7.26%	6.01%	5.96%	3.33%
5.77	3.06	3.63	2.06
15.70	17.50	18.19	22.80
2.91	2.58	1.68	3.86
16.40	7.96	10.29	0.82
4.86	2.43	3.57	0.00
10.19	4.95	6.40	0.50

presumed that much, if not all, of the Peruvian material studied by Unger was old, and from North Chincha Island. Phipson (1862, 1863), who claimed to have found xanthine

chemischen Technologie," three analyses of Peruvian guano, one containing 13.48% (COO)₂. Since this sample allegedly contained 1.06% ammonium bromate, a most improbable constituent, particularly when only 0.40% NaCl is reported, all three analyses, the source of which could not be traced, are suspect and of little interest.

in Jarvis Island and West Indian guanos containing, at the most, but a trace of uric acid, indicates that xanthine had apparently been met with in other guanos also; his statement, however, probably reflects the initial confusion, though he was clear that the substance that he isolated was not Unger's guanine.

The significance of the three analyses of guanos (IV, V, VI) given by Raimondi (1878) is problematical, because an enormous amount of organic matter, not accounted for as uric acid or as oxalate, appears to be present, and the quantity of oxalate recorded is unaccountably low. The analyses are primarily of interest in showing a similarity between Chinchá Island guano and that from Chanavaya which will be discussed on a later page (p. 106). It is very improbable that these analyses are reliable, though it is conceivable that some of the so-called organic matter was ammonium bicarbonate, which occurred as a discrete mineral in the deposits (p. 93). Where ammonia as an ammonium carbonate has been allegedly determined in ordinary guano samples, as in the next series, it is, however, present in relatively small amounts.

PARTIAL ANALYSES OF OLD PERUVIAN GUANOS

An enormous number of partial analyses of old insular guano must have been made, of

	CHINCHA	GUAÑAPE	BAL- LESTAS
Water	14.81%	21.63%	22.96%
Organic matter and NH_3 salts	52.38	36.24	41.96
CaO	10.99	11.32	10.53
MgO	1.19	0.80	1.01
K ₂ O	2.28	3.68	2.81
Na ₂ O	1.35	2.78	2.86
Fe ₂ O ₃	0.30	0.45	0.21
P ₂ O ₅ total	13.52	13.39	13.14
P ₂ O ₅ sol.	2.75	4.36	3.26
SO ₃	2.09	3.12	0.77
Cl	1.25	1.33	2.08
SiO ₂	1.76	6.30	1.67
N total	14.39	9.30	12.19
N as ammonium carbonate	1.25	0.89	1.32
N not as vol. am- monium salts	?	5.39	4.12

which number only a small fraction can have been published. The three (column 1, this page) from Heiden (1887) are somewhat more complete in their enumeration of inorganic constituents than are most of the analyses that appeared in print.

The majority of the published analyses are much less detailed, only constituents of supposed argicultural significance having been determined. The interesting analyses of this class are summarized in table 6.

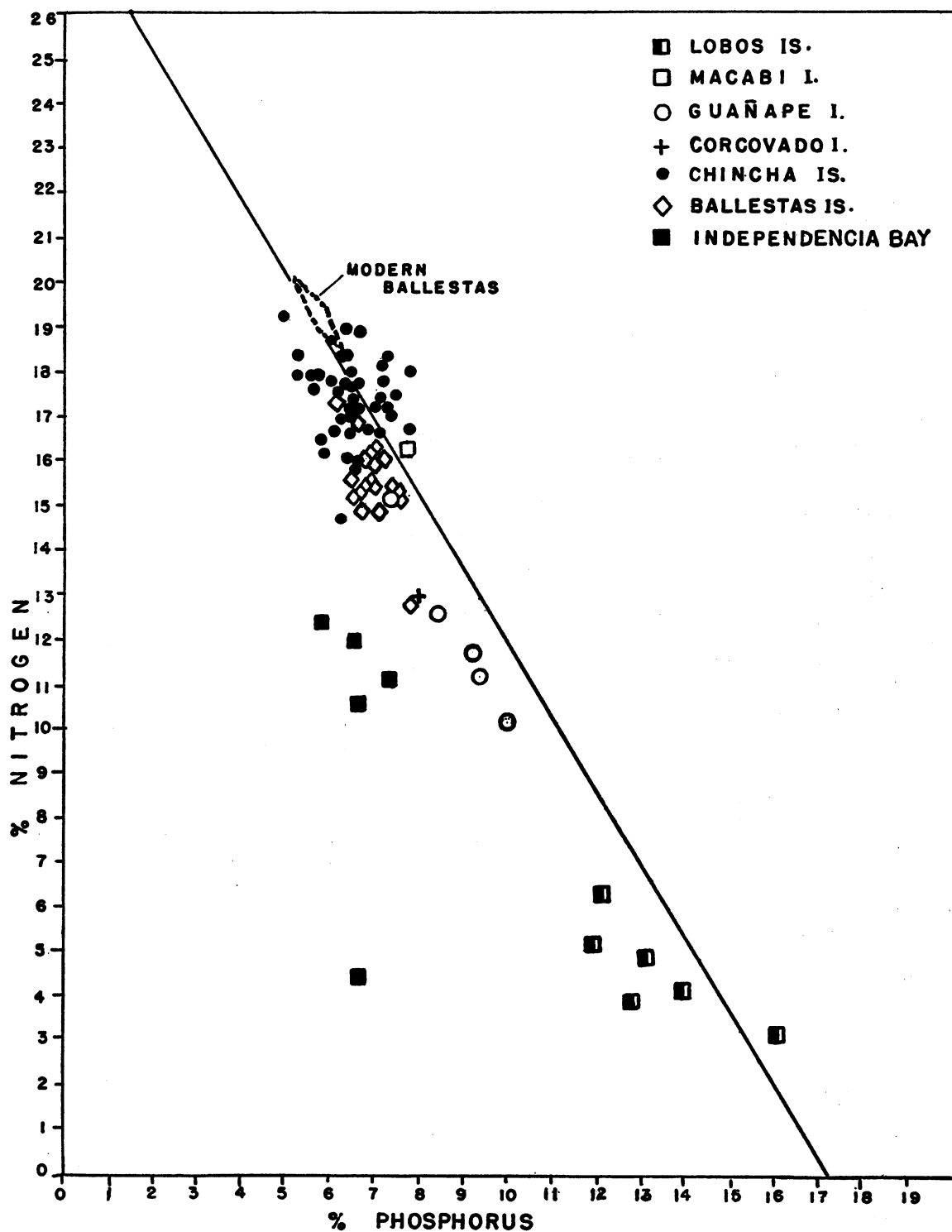
RELATIONSHIP OF NITROGEN TO PHOSPHORUS CONTENTS OF OLD PERUVIAN GUANOS

The nitrogen and phosphorus contents of these samples are plotted on a moisture-free and sand-free basis in figure 21. The regression line from figure 20 is also drawn on the same diagram. The disposition about the regression line of the points representing Nesbit's series of Chinchá Island guanos, some of which must have been of considerable age, is most striking. Not merely do these points exhibit a degree of decomposition little greater than that of the modern Ballestas samples, indicated by the pecked envelope, but such change as has occurred has proceeded, so far as the total nitrogen is concerned, exactly as it would have done during a few years on the islands at the present time. The points for the slightly more decomposed ancient Ballestas guanos and the still less nitrogenous Guañape and Macabí guanos again show a striking tendency to fall along the regression line, and only in the case of the Independencia Bay samples is there any marked divergence. Two explanations of such divergence are possible: either the nitrogenous compounds lost proportionately more nitrogen than other elements, or some material was added to the guano. There can be little doubt that the latter explanation is correct, for it appears from Fallon's remarks on Santa Rosa guano that it was deliquescent, owing to modification by the salt spray of the sea. Fallon's analyzed sample, represented by the lowest point for Independencia Bay on the diagram, is poor in nitrogen and contained no less than 14.73% Cl. It thus represents to an extreme degree the condition evidently indicated by Voelcker's analyses.

TABLE 6

	Moisture	Total N	Organic Matter (+NH ₃ salts)	Total P ₂ O ₅	CaO*	Alk. Salts (less sol. P ₂ O ₅)	Sand, SiO ₂
Macabí (Mean 1863 samples; Raimondi, 1897)	—	6.58%	—	14.95%	—	—	1.72%
Macabí (Mean 25 analyses by Ohlendorff Co. com- municated to Heiden, 1887)	30.33%	11.05	—	11.95	—	—	1.72
Guañape (Ohlendorff-Heiden, as above)	25.88	11.00	—	12.25	—	—	1.92
Guañape (Shepard, 1870b, 2 anal- yses)	27.75 23.10	8.32 8.43	35.48% 38.53	14.80 16.13	— —	— —	1.53 1.46
Guañape (Voelcker, 1860, 2 anal- yses)	17.79 20.10	10.04 7.84	42.62 38.67	16.41 17.64	12.79% 17.62	7.17% 3.24	2.22 2.73
Corcovado I. (Aikman, 1894)	—	10.57	—	14.53	—	11.60	—
Corcovado I. (Fallon, 1899)	17.25	10.41	40.65	14.61	—	7.55	2.66
Chincha Is. (Mean and extremes, 48 analyses of unspoiled guano, Nesbit, 1860)	15.67 11.40– 20.20	14.41 12.55– 16.22	52.92 46.75– 62.30	12.11 8.83– 14.67	10.52 8.18– 13.81	7.50 1.92– 16.89	1.26 0.65– 2.50
Ballestas (Mean and extremes, 17 analyses, Voelcker, 1872)	17.65 13.48– 19.28	12.68 10.75– 13.60	48.58 46.56– 51.01	12.89 11.94– 14.87	12.05 11.18– 13.74	7.21 5.14– 9.50	1.78 1.29– 2.84
Ballestas (Ohlendorff-Heiden, as above)	14.87	12.50	—	12.23	—	—	3.24
Independencia Bay (Probably S. Rosa I., Ohlendorff-Heiden, as above)	12.00	7.05	—	11.85	—	—	16.10
Independencia Bay (Probably S. Rosa I., mean and extremes 4 analyses, Voelcker, 1877)	8.69 8.17– 9.74	7.89 7.33– 8.53	34.62 31.86– 36.97	10.25 9.17– 11.16	10.91 10.03– 11.88	12.59 12.01– 13.61	22.94 19.25– 25.05
S. Rosa I. (Modified by salt spray, Fallon, 1899)	12.4	3.6	17.98	12.32	35.74		6.90

* In the analyses by Voelcker, the CaO has been calculated from the Ca₃P₂O₈ given; this procedure seems safe in the case of any sample for which P₂O₅ in excess of that present as triphosphate is recorded.



ALKALINE SALTS

The ash constituents other than calcium, which was evidently present mainly as phosphate and oxalate, are little known. It appears that magnesium, sodium, and potassium were all present in quantities at least of the order of magnitude of 1%, and the minimum amount of chloride would seem to be of the same order of magnitude. Where very large amounts of chloride and sodium are present, as in analysis IX of Denham Smith's saline guano which may have contained up to 35% NaCl, there is presumptive evidence of modification by sea water, but in the case of normal specimens low in chloride there is every reason to suppose that the Na, K, Mg, and Cl present are obtained from the food of the birds. The only analyses of any clupeid fish complete enough to be of interest in this connection are those of Dill for eviscerated, decapitated *Sardinops caerulea*. Sodium determinations are lacking, but from the data collected by Vinogradov (1944) the Na₂O content is not likely to exceed twice the K₂O content. The means of Dill's two series of determinations are:

	WET WEIGHT
K ₂ O	0.360%
CaO	0.477
MgO	0.045
P ₂ O ₅	0.408
SO ₃	0.045
Cl	0.164

It is reasonably certain that, owing to the over-representation of muscle and the probable loss of blood, the potassium figure is excessive, and that, owing to the decapitation, all the figures save that for CaO are too great relative to P₂O₅. If the proportions implied by the analysis are calculated for a guano containing the modal P₂O₅ content of 10.5%, the guano should contain:

K ₂ O	9.26%
CaO	12.00
MgO	1.16
P ₂ O ₅	10.50
SO ₃	1.16
Cl	4.22

Even if the potash figure is four times too great and the chloride twice too great, there would still be enough potassium, chloride, and presumably sodium in the food to supply

more than the observed amount in the guano. There is thus no evidence from the available data that the guano birds drink any appreciable amount of sea water.

SAND CONTENTS OF GUANOS

Material referred to in analyses as sand or insoluble siliceous matter, or sometimes merely as silica, is always present. In some poor specimens it is abundant, but in the rich nitrogenous deposits the amount is of the order of 1%. The series of 48 good samples analyzed by Nesbit give the following distribution:

NO. OF SAMPLES	SILICA CONTENT
11	0.00%–0.95%
34	1.00 –1.95
3	2.00 –2.95

The rather narrow limits of variation in the sand content, when compared with the variation of the alkaline salts, which are doubtless mainly extraneous and of marine origin, suggest that the presence of about 1% sand in the old guano was not due to accidental events. Peacock (1874) made the interesting suggestion that the quantity of sand normally present in guano represents material purposely ingested by the birds.

FLUORINE CONTENTS OF GUANOS

The fluorine content of a number of Peruvian guanos was studied by Braun (1896), who found in two Peruvian guanos of unspecified origin 0.05% and 0.20% F, while a specimen from the Chincha Islands gave a value of 0.14% F. A material termed "caliche guano" which may have been Chilean contained 0.34% F, while undoubted Chilean guano from Huanillos contained 0.25%. The differences apparent in comparing the Peruvian and the supposed Chilean guanos are interesting, the older Chilean samples being slightly higher in fluorine. The significance of the differences is, however, reduced by the fact that an African sample is said to have contained 0.26% F. The whole of Braun's data is, moreover, of very doubtful validity, because for various samples of phosphate rock he obtained what seem to be impossibly high values, 1.4 to 2.0 times those obtained by more recent workers. Jacob, Hill, Marshall,

and Reynolds (1933), however, confirm the general order of magnitude of Braun's analyses by finding 0.06% F in fresh Peruvian guano containing 14.40% P_2O_5 corresponding to a ratio F: P_2O_5 of 0.0042.

BORON CONTENTS OF GUANOS

This element has been determined in only two atypical samples. The first specimen, described as "guano excrement from the Moro Arica," kindly given me by Dr. Robert Cushman Murphy is very contaminated with chloride and contains 40.2% sand, 7.0% CaO, and 3.8% P_2O_5 . Dr. Gordon H. Ellis found this specimen to contain 68 γ B per gram. The second sample is brown pulverulent material adhering to the mummified remains of birds obtained by Shepard from the cargo of Guafape guano that he examined. These specimens were sent to the Peabody Museum at Yale and through the kindness of Dr. George F. Eaton, who knew of their existence, and of Dr. Stanley C. Ball, Curator of Zoology, they have been available for examination. The material in question is obviously not typical guano and appears microscopically to consist largely of fragments of mummified bird tissue; it is obviously well impregnated with inorganic material and contained:

H ₂ O and ignitable matter	45.1%
CaO	20.0
P_2O_5	21.9
Sand	2.7

a composition indicating considerable enrichment in calcium phosphate over Shepard's analysis of Guafape guano derived from this cargo. The boron content of this material was found by Dr. Ellis to be 19 γ per gram, which is probably a better value for the boron in old guano, but again the nature of the material precludes the estimate's being representative.

RELATION OF GUANO PRODUCTION TO FOOD SUPPLY

It has already been pointed out that Vogt's careful study indicates that each adult that starts a successful breeding season is responsible for the production of 15.9 kilograms of guano, as normally collected, during the ensuing year. Tschudi's observations indicate a like order of guano production by *Sula*

variegata. It has, however, been pointed out that Vogt's estimate is probably too high, as it may well include some guano deposited by young birds that have already started to fish but that, returning to the island, may increase the population density for a time above the nesting density. Vogt assumed that from this figure for guano production and from his estimates of the food intake of the birds the food required to produce unit mass of guano or to produce the entire annual crop of the Peruvian coast could be computed. Owing to the fact that all guano collected on the islands appears to have lost some nitrogen, such a method of computation is unsound.

It is more satisfactory to compare guano production with food intake on a biochemical basis. The fundamental data for this comparison are, however, not fully available, and approximations to certain of them are at present inevitable. No information exists as to the chemical composition of *Engraulis ringens*. For *E. encrasicolus* Vinogradov (1944) summarizes seven determinations of nitrogen falling between 2.17% and 3.49% of the live weight, the mean being 2.74%. He also quotes two determinations of phosphorus, namely, 0.2161% and 0.47%, of which the mean is 0.343%. The N:P ratio derived from these means is 8:1. The lower phosphorus value (Carteni and Aloj, 1934) is derived from the edible part of the fish only, presumably excluding the head. Dill gives for decapitated, eviscerated *Sardinops caerulea* even lower mean contents of but 2.69% N and 0.179% P, implying a ratio of 15:1. The high phosphorus content of 0.47% for *E. encrasicolus* (Minder, 1933) corresponds to the lowest nitrogen content and a ratio of 4.6:1. This suggests that Minder's fish were in rather poor condition. Examination of all the data assembled for the Clupeidae by Vinogradov indicates that the most probable values for any species of the family would be about 3% N and 0.3% P, with a ratio of approximately 10:1. Such values will be referred to below as the most probable for the nitrogen and phosphorus in the food, though the limits apparently set by Minder's and by Dill's analyses will also be considered.

For quite fresh bird droppings only Coker's analysis of pelican excrement, giving 21.66% N and 1.88% P and a ratio of 11.5:1, is available; the ratio is in reasonable agreement

with the most probable value for the food. For modern commercial guano as collected today on the islands, the modal phosphorus value (Buzaglo, 1930) of 10.5% P_2O_5 or 4.59% P may be used.

Forbes (1914a) gives data that indicate that in captivity *Sula nebouxi*, which, following the practice in the extreme north of the guano coast, he calls the piquero, produces unit mass of undecomposed guano from 5.7 units of food. Nothing whatever is said about the dryness or chemical composition of the guano, but if the food contained the most probable amount of nitrogen and phosphorus, the resulting guano would have contained 17.4 % N and 1.74% P, which is not unreasonable. More food would of course be needed to produce unit mass of commercial guano containing less nitrogen.

A more recent experimental study on captive guanays has been made by Gamarra Dulanto (1941). In this study the guano production per unit mass of food was determined by comparing the production of starving birds with birds fed a known quantity of food; the guano produced was apparently much contaminated with sand, feathers, etc. The actual figures from this experiment are as follows:

	GRAMS
Weight of excreta of 6 birds fed 546 grams of fish	169
Twice weight of excreta of 3 unfed birds	109
Difference	60
Sand and feathers	27.1
Guano allegedly derived from 546 grams of fish	32.9

Gamarra Dulanto concludes from this experiment that 16 tons of fish are consumed to produce 1 ton of guano as collected on the islands. He also believes that for every ton deposited on the island 1 ton is lost to the sea so that in practice 32 tons of fish rather than 16 are eaten for every ton of guano that is collected. The experiment in which no metabolic balance is achieved and the controls are obviously unwillingly converting themselves into guano gives no support to the first conclusion, even though it is probably essentially correct. The second conclusion, not even supposedly based on the ex-

periment, is almost certainly wrong, as will presently appear.

Vogt concluded, from his experiences at the Ballestas Islands, that one adult guanay was responsible for the production of 15.9 kilos of commercial guano per year, or 43.5 grams per day. This material may be taken to contain 15.32 % N and 4.64% P, as did the Ballestas guano analyzed for Coker. The N:P ratio of 3.3:1 is here so low that nitrogen must have been lost, as has already been established, and only phosphorus can be considered in the calculation.¹ Assuming the food to contain 0.46% P, Minder's value for *Engraulis encrasicolus*, which is almost certainly excessive as a mean value for the food of the guanay, 430 grams of fish must be ingested daily. If the most probable value for the food, namely, 0.3%, is used, the intake would have to be 673 grams; for lower phosphorus contents, even greater quantities of food would have to be eaten. As has previously (p. 18) been indicated, Vogt considers that the maximum catch made by a guanay in a day is not likely to exceed 316 grams. Part of the discrepancy between this figure and that derived indirectly from the guano output is probably due to the fact indicated above that the actual production per bird of mean age is almost certainly less than 15.9 kilograms. It is also possible that Vogt's estimate of the food captured was lower than normal because of lower than normal supply of fish at the time that he made his observations, and that if stomach contents had been available from birds over a long period of several seasons, the food intake would have been higher. Whatever the nature of the discrepancy it is reasonably clear that *Phalacrocorax bougainvillei* produces at least as much guano as could reasonably be expected from its food supply.

Gamarra Dulanto's contention that half the guano produced by a guanay is lost at sea would appear to lead to a quite impossible food intake—at least 860 grams per day. It would strain the explanations of the discrepancy between Vogt's estimates of food intake and of guano production to the break-

¹ Boussingault (1860a), in the only previous biochemical consideration of the matter, used nitrogen contents and arrived at the result that 6 tons of fish produce 1 ton of commercial guano. This conclusion is obviously incorrect.

ing point if they had to be extended to cover twice the guano production that Vogt observed. Loss of guano due to excretion over the sea is obviously not a significant factor in reducing deposition on the islands. It is reasonable to suppose that the excreta are retained until the bird is on land and so can make use of them in nest construction during the breeding season. It is in fact not impossible that a tendency to development of such behavior in the Pelecaniformes underlies the fact that these birds rather than the gulls and terns are the chief guano birds.

On the basis of the modal phosphorus content for the whole coast the quantity of fish required to produce 1 ton of commercial guano will be 9.8 tons if Minder's phosphorus content of 0.47% be accepted, 15.3 tons if the most probable value of the composition of the food be used, and even more if the food be supposed to have a lower phosphorus content. These estimates, which are independent of the number of birds, imply that to produce a large annual guano crop of, for example, 150,000 tons, which amount may on occasions be exceeded, at least 1,460,000 tons of fish, and probably considerably more, must be eaten by the birds. This vast minimum catch is, however, more than is considered a safe yield, permitting permanent exploitation, of the California sardine, which lives under conditions not unlike those constituting the environment of *Engraulis ringens*. This consideration suggests that at its height the guanay population probably converts as much fish into guano as is consistent with an indefinite persistence of all the parts of the ecosystem concerned.

It seems unlikely that any fishery intended to furnish a highly developed artificial fertilizer industry could be set up without competing with the birds and without depleting the fish population to a dangerously low level. Gamarra Dulanto considered that in producing guano from fish 1 ton of guano, which costs S/34.00 to produce and is valued at S/104, is equivalent to 8 tons of fish-meal. Actually, the argument given above indicates that the equivalent should be 4 rather than 8 tons. Four tons of fish-meal would be valued at S/332.50 and would cost S/67.36 to produce. The profit when both were used locally would be S/35 from guano,

S/265.64 for fish-meal. In long-range economic terms, however, this is not likely to be the whole story. The size of the maximum population of guanays may be regarded as more or less self-regulatory. Without much further study, introducing a competing fishery to feed a large fertilizer industry that would have to maintain its output even when fish were hard to obtain would be the height of folly, undoing the work of almost half a century of conservation and reintroducing into the guano industry the saturnalian element that all intelligent Peruvians deplore. Vogt's (1942) and Murphy's (1944) warning against such a policy of wholesale expansion of the fish-meal industry should be given the most serious consideration by all concerned with the welfare of the birds and their precious excrement.

PHOSPHATIC AND LEACHED GUANOS

The persistence of guanos rich in nitrogen is possible only under very dry conditions. When the aridity is extreme, as in the southern part of the Peruvian coast, the accumulations of guano are quite stable, but wherever rainfall, however restricted, is a normal annual event, decomposition, solution, and mechanical erosion may be expected to modify the deposit further than do the processes already considered. If the rainfall is excessive, all the material will be washed away and ultimately returned to the sea; this process is of no interest in the present context. Under less extreme conditions, decomposition, solution of both original and secondary constituents, and the subsequent migration of the solutes give rise to various kinds of phosphatic guanos, which are far more widely distributed than are the nitrogenous deposits and consequently will be the subject of the greater part of the present monograph. On the Peruvian coast such guanos occur on the Lobos Islands and in a few other localities. They are not important commercially in the region, but since in Peru they are encountered along with more nitrogenous deposits, it is convenient to consider in this place the general aspects of the relationship of the phosphatic guanos to the nitrogenous, though some of these general aspects will have to be considered again and again throughout the present work.

Four processes appear to be possible:

1. Decomposition *in situ* leads to a loss of organic matter and of ammonia, so that the remaining material is enriched in non-volatile inorganic material, mainly calcium phosphates. This type of decomposition has already been considered in relation to the nitrogen:phosphorus ratio. The condition for such decomposition is certainly the presence of water, and it is presumably much augmented by high temperatures. Great excess of precipitation, however, will remove most or all of the deposit mechanically or initiate the changes of the succeeding types. This type of diagenetic change will therefore be most conspicuous in warm climates of low, and usually strictly seasonal, rainfall. Dixon (1878b) observed that on Malden Island the odor of ammonia disappeared from deposits formed by breeding birds within three months of the end of the breeding season, without rain having fallen. This observation, together with the very low values (9.35% to 14.10%) for organic matter that he records in supposedly fresh guano of *Fregata*, *Sterna*, and *Puffinus*, suggests that in hot sunshine far more extensive diagenetic losses than have yet been considered occur *in situ* without leaching, provided the air is not too dry. Dixon's conclusions are, however, not entirely acceptable because his analyses seem to suggest that the phosphate in the final product is present as $\text{Ca}_3\text{P}_2\text{O}_8$, or more probably as an apatite-like substance, but definitely not as CaHPO_4 , some of which substance would be expected in the absence of leaching. As is indicated below, a process of decomposition *in situ* certainly does occur in the Lobos Islands.

2. Percolating water will remove the more soluble constituents of the guano. Stutzer (1911) quotes some results referred to H. Bross (*sic*, ?=H. Voss), indicating how the processes of leaching and decomposition can be imitated in the laboratory. A sample of nitrogenous guano originally contained:

Moisture at 100°C.	21.44%
Organic matter, ammonium salts, and water of constitution	40.46 (N = 9.76%)
P_2O_5	13.98
CaO	12.38
Other soluble constituents	9.79 ($\text{K}_2\text{O} = 2.83\%$)
Insoluble siliceous matter	1.95

After washing and ignition, the material, which must have lost about two-thirds of its mass, contained:

H_2O	0.02%	0.35%
Organic matter	0.70	3.10
$\text{Ca}_3\text{P}_2\text{O}_8$	53.57	49.07
CaHPO_4	23.39	23.31
Magnesium phosphate ($?\text{Mg}_3\text{P}_2\text{O}_8$)	4.95	3.30
(Al,Fe) PO_4	6.15	7.60
Alkalis	5.18	7.51
Insoluble siliceous matter	6.04	5.76

The kind of solution produced by leaching a practically undecomposed guano is indicated by Raimondi's analysis of the liquid guano of Guafape, given below (p. 91). Calcium is apparently absent, probably being retained in the solid phase as oxalate. Moreover, owing to the incongruent solubility of all calcium phosphates less basic than hydroxylapatite, continued action of water on a fully decomposed guano, such as that obtained experimentally by ignition and washing, will tend to remove more phosphorus than calcium as the solid phase approaches in composition the congruently soluble hydroxylapatite.

3. The solutions that have passed through guano, if they are not lost to the ocean, may evaporate, depositing various inorganic salts as minerals according to the stage of decomposition reached by the guano. In cases where the solution approximates the liquid guano of Raimondi, the water-soluble salts, sulphates, phosphates, and oxalates of alkalis and of ammonia, known from the Peruvian nitrogenous guanos, will be deposited. Evidence will be given from Mejillones (p. 118) that the leaching of somewhat more decomposed guanos by sea spray commonly results in deposition of various magnesium phosphates. Even if all the bacterial decomposition that can occur *in situ* has taken place before leaching begins, the solution at first will contain more phosphate relative to calcium than the solid phase, and CaHPO_4 , either anhydrous or hydrated, may be expected to form on evaporation.

4. The solution may be neither lost nor evaporated but may attack the underlying rock, producing metasomatic phosphatization. No certain evidence of this process is known from the Peruvian coast, but in other

parts of the world the phosphatization of coral rock producing calcium phosphate minerals, and of various igneous rocks producing ferric and aluminum phosphate minerals, is a biogeochemical process of importance.

The most important deposits of phosphatic guano on the Peruvian coast are on the two most northern islands, Lobos de Tierra and Lobos de Afuera. Considerable quantities of more or less decomposed guano are still apparently available and are intermittently dug on these islands; much of this material is contaminated with a large amount of sand. The analysis by Cancino given below has been recalculated on a sand-free basis, as it originally contained 36.65% sand. It may be instructively compared with Coker's analysis of fresh pelican droppings and of modern pelican guano, also recalculated on a sand-free basis.

N·NH ₃	1.67
N·uric acid	0.28
N·purine	0.58
N·NO ₃	0.42
N·keratin	0.00
Org. C	2.50
Org. C not accounted for	1.70
Org. matter directly det.	6.8
Org. compounds + twice org. C not accounted for	5.6
Matter not ash, NH ₃ , H ₂ O, or directly det. org.	12.1

The rather large amount of material not accounted for is curious. The purine fraction, relative to the total nitrogen, is definitely higher than in undecomposed guano, the purine nitrogen being 19.6% of the total, while it is not known to exceed 13% in modern nitrogenous guano. This observation perhaps is in accord with Phipson's (1862) old record of the presence of xanthine in guano so

	<i>Pelecanus o. thagus</i> , DROPPINGS OF CAPTIVE BIRD (COKER, 1919)	LOBOS DE AFUERA, MODERN <i>P.o.</i> <i>thagus</i> GUANO (COKER, 1919)	LOBOS DE TIERRA, OLD PHOSPHATIC GUANO (CANCINO, 1935)
Water	9.48%	17.76%	19.42%
Organic matter	82.22	48.26	13.78
N total	21.86	9.25	2.65
N·NH ₃	—	—	0.91
N·NO ₃	—	—	0.12
N org.	—	—	0.65
P ₂ O ₅ total	4.34	19.14	28.57
P ₂ O ₅ water sol.	—	—	0.96
P ₂ O ₅ citrate sol.	—	—	11.82
CaO	—	—	22.15
K ₂ O	—	—	2.21

Popp and Marxen (1931) have given an analysis of a phosphatic guano from Peru, which can be identified by the nitrogen fractionation, repeated by Cancino, as coming from Lobos de Tierra:

Water	14.0 %	
Total ash	65.1	
CaO	17.4	
MgO	2.8	
K ₂ O	1.09	
Cl	1.05	
P ₂ O ₅ total	19.27	
P ₂ O ₅ citric acid sol.		17.00
P ₂ O ₅ ammon. citrate sol.		2.60
Acid insol.	23.8	
Ash unaccounted for	-0.31	
Oxalic acid	0.09	
N total	2.65	

decomposed as to have lost all its uric acid. The high relative nitrate in the Lobos de Tierra guano is probably characteristic. Popp and Marxen point out that if, as they believe to be true in other cases, the citrate-soluble phosphate is assumed to be CaHPO₄ and the rest of the phosphate to be Ca₃P₂O₈, the amount of calcium required is greater than that found. They suggest that magnesium phosphate is present. The molecular ratio of CaO:P₂O₅ is 1:0.508 for Cancino's sample and 1:0.437 for that of Popp and Marxen. While it is improbable that the proportion of different phosphate minerals can be calculated from the solubilities, the ratios given are in accord with the greater proportion of citrate-soluble phosphate in Cancino's sample than in Popp and Marxen's specimen.

THE MINERALOGY OF NITROGENOUS GUANO

The formation of discrete differentiated minerals in guano is of some interest. The existence of such minerals in nitrogenous guanos implies the occasional existence of water percolating through the mass. Raimondi (1878) has pointed out that distinct mineral aggregates were found more commonly in the Guañape than in the Chincha deposits, the former locality being slightly less arid. He also gives an analysis of a liquid guano found in a cavity in the rock below the Guañape deposit. This liquid, of the color of tincture of iodine, had a fetid ammoniacal odor, like a mixture of ammonia and volatile fatty acids. Analysis gave:

	GRAMS PER LITER	PER CENT
K ₂ O	36.76	3.02
Na ₂ O	13.34	1.09
(NH ₄) ₂ O	90.50	7.43
SO ₃	61.10	5.01
CO ₂	31.00	2.54
P ₂ O ₅	57.20	4.70
Cl	25.70	2.11
Fatty acids, water, indet.	903.00	74.10

This analysis is of considerable interest as indicating the kind of mother liquor from which the crystalline minerals of nitrogenous guano were deposited. The minerals recorded are listed below; it has seemed desirable to separate those known as pseudomorphs of birds' eggs, several special names of doubtful validity having been applied to them.

MASCAGNITE

According to Raimondi (1878), (NH₄)₂SO₄ occurred in Guañape Island guano as small crystalline masses, often in cavities. The poorly differentiated crystals gave the material a radiate appearance. The mineral was usually associated with oxammite. No quantitative analysis was given, but as the material was completely volatile the identification is reasonable.

ARCANITE

Shepard designates as "pure sulphate of potash (Aphthitalite)" minute scaly crystals abundantly associated with taylorite on mummified birds from Guañape, but typical aphthitalite contains sodium. The record

must be regarded as very doubtful in the absence of any description of optical or chemical properties.

TAYLORITE

A potassium ammonium sulphate, typically about 5K₂SO₄·(NH₄)₂SO₄, analysis giving (Taylor, 1859):

SO ₃	48.40%
Na ₂ O	1.68
K ₂ O	43.45
(NH ₄) ₂ O	5.37

and a trace of organic matter. The mineral occurred as small crystalline concretions in Chincha Island guano. Shepard records taylorite from the spinal canal, cranium, and stomach of mummified birds from Guañape Island. A chemically similar substance containing more ammonia, about 4K₂SO₄·(NH₄)₂SO₄, has been recorded by Warrington (1845) replacing bones in Ichabo guano. He supposed that the potassium came from the ashes of fires lit by seal hunters, but it is clear that the formation of potassium sulphate minerals is general in nitrogenous guanos.

No type material of taylorite now appears to be known in collections. Dr. Horace Winchell has examined several specimens supposedly of taylorite, from the Chincha Islands and from undesignated Peruvian localities, and finds them to give X-ray powder patterns essentially identical with that of ordinary K₂SO₄. The mineral of the fossil *Pelecanoides* egg designated as belonging to the American Museum of Natural History in table 7 gives a similar diffraction pattern. It is evident that one of the two commonest minerals in the old guano deposits was a sulphate, mainly of potassium, but containing smaller quantities of ammonium and sodium. To this mineral the name taylorite may conveniently be applied, at least provisionally. It is hoped that a full discussion of the problem of taylorite will shortly be forthcoming from Dr. Winchell and Mr. R. J. Benoit.

GUANAPITE (SHEPARD, 1870)

Described as a potassium ammonium sulphate with a small amount of oxalate, the composition being given as K₂SO₄ 67.75%, (NH₄)₂SO₄ 27.88%, (NH₄)₂C₂O₄ 3.75%. The material occurred in reddish balls and veins throughout the Guañape deposit. In view of

Raimondi's remarks about the intimate association of mascagnite and oxammite in this locality, it is very doubtful that guanapite was a homogeneous substance. It may perhaps be a mixture of ammonium-rich taylorite and a little oxammite.

OXAMMITE = GUAÑAPITE OF RAIMONDI (1878)

Natural ammonium oxalate evidently occurred freely in the Guañape deposit. The name was put forward by Shepard (1870) for small crystals associated with mummified birds and identified as ammonium oxalate by qualitative methods without a quantitative analysis. Raimondi says that ammonium oxalate freely occurred, mixed with mascagnite, at Guañape, often in cavities in the guano. A lump was analyzed by Tanner (1875) who concluded that the mineral had the composition $(\text{NH}_4)_2\text{C}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$. Though such a hydrate is otherwise unknown, this composition has been given in treatises on mineralogy, as, for instance, Dana (1892).

	NH_3	C_2O_4	H_2O
	20.73%	50.35%	23.38%
The supposed formula requiring	21.25	55.0	22.5

Specimens of oxammite were recovered from Shepard's mummified birds in the Peabody Museum, Yale, and a large fossil egg in the mineralogical collection of Columbia University, though labeled guanovulite, proved to consist of the mineral. Specimens from both sources give X-ray diffraction powder patterns identical with ordinary ammonium oxalate monohydrate $(\text{NH}_4)_2(\text{OOC})_2 \cdot \text{H}_2\text{O}$. This formula is consistent with the analysis of the mineral of the fossil egg (table 7) which contained oxalate equivalent to 63.44% $(\text{NH}_4)_2(\text{OOC})_2$, a slight excess of ammonium as well as some potassium and sodium being assumed present as sulphate and phosphate. This amount of ammonium oxalate implies 9.22% H_2O for the monohydrate, 18.44% for the dihydrate. The analysis gives 8.85% water of hydration by difference, which is obviously in far better agreement with the monohydrate than the dihydrate. An account of oxammite, giving the physical data of mineralogical interest, will shortly be published by Dr. Horace Winchell and Mr. R. J. Benoit.

In 1869, when borings to ascertain the depth of the deposit were made, a band 2 to 2.3 meters thick was encountered in the middle of the guano, having the composition:

NH_3	17.82%
Oxalic acid	24.80
H_2O	26.95
Uric acid	0.50
SO_3	2.60
CO_2	1.30
P_2O_5 sol.	0.10
Cl	1.20
$(\text{Na}, \text{K})_2\text{O}$	0.80
$\text{Ca}_3\text{P}_2\text{O}_8$	4.90
Org.	19.03

The great excess of ammonia is recorded without comment. If the analysis is reliable, some of this ammonia must have been present as organic nitrogen or as salts of undetermined organic acids.

WHEWELLITE

Calcium oxalate monohydrate, $\text{CaC}_2\text{O}_4 \cdot \text{H}_2\text{O}$, termed by Shepard oxycalcite, is recorded by him as occurring very rarely, attached by a point to thin shreds of the tissues of mummified birds from Guañape.

PHOSPHAMMITE

Ammonium phosphate is recorded without analysis as forming small white masses in Chincha Island guano (Raimondi, 1878) and almost transparent lumps in Guañape guano by Shepard. The latter states that phosphammite formed on the bony remains of birds and seals exposed to the air and on further exposure lost ammonia, forming biposphammite. No analyses are given. Ammonium phosphate is also recorded, as crystals, in Ichabo guano by Herapath (1849), who purified his material by recrystallization and obtained:

NH_3	23.980%
P_2O_5	52.962
H_2O	23.058

No analysis of the mineral in its natural state seems to have been published.

STERCORITE

Natural microcosmic salt, $\text{NaH}(\text{NH}_4)\text{PO}_4 \cdot 4\text{H}_2\text{O}$, was found as crystalline masses in Ichabo and Guañape guano. Analyses give:

	ICHABO (HERAPATH, 1849)	GUAÑAPE (RAIMONDI, 1878)
(NH ₄) ₂ O	7.68%	8.48%
Na ₂ O	15.75	14.50
P ₂ O ₅	34.33	34.54
H ₂ O	42.24	42.48

The analyses indicate a slight deficiency of ammonia and a slight excess of water. The Guañape occurrence was almost immediately over the bedrock, in large, transparent, colorless or pale yellow crystals. The mineral also occurred at Guañape as crystalline masses coating the "shrivelled skins and intestinal membranes" of mummified birds.

"CALCIUM PHOSPHATE"

Recorded without analysis, and of uncertain mineralogical character, in lumps smelling of ammonium carbonate in Peruvian guano and in purer masses in Bolivian (i.e., probably Mejillones) guano (Baudrimont, 1873).

TESCHEMACHERITE

Essentially natural ammonium bicarbonate. The first record (I) was from Ichabo Island (Teschemacher, 1846), but it was subsequently noted from Patagonia (II) by Ulex (1848), from the Chincha Islands (III) by Phipson (1863), and from both the Chincha Islands and Guañape Island by Raimondi (1878). The amorphous (IV) material analyzed by the last-named investigator appears to have come from Chincha; his crystalline material, in cavities (V), from Guañape. Analyses, assuming Teschemacher's ammonia to be (NH₄)₂O and disregarding small amounts of calcium salts, phosphate, sulphate, etc., give:

	I	II	III	IV	V	(NH ₄)·HCO ₃
(NH ₄) ₂ O	33	30.06	29.76	31.62	32.21	32.90
CO ₂	56	54.35	51.53	55.70	55.90	55.7
H ₂ O	11	11.92	11.00	12.68	11.09	11.4

indicating a uniform material diverging little from the theoretical composition. Phipson, however, noted that his specimen smelt strongly of ammonia and assumed some sesquicarbonate or normal carbonate to be present. Phipson records that his material occurred at the bottom of the Chincha deposit, where the mineral formed a white

layer several inches thick under the guano. Boyd (1893) indicates that the mineral was of economic significance, as "quantities of carbonate of ammonia are picked out of the loose guano, and often large lumps of snowy whiteness are discovered by the convict workers, and secreted by them until a favorable opportunity occurs for exchanging them for pieces of ship's pork." The Patagonian locality is said to have yielded the salt in commercially workable amounts. Ulex expressed surprise that the salt should occur in a humid region, but a record by Malaguti (1861) of rare ammonium carbonate crystals may possibly confirm the occurrence (p. 357).

SALAMMONIAC

Or natural ammonium chloride, recorded by Raimondi (1878) as having occurred in the guano of the Chincha Islands.

PSEUDOMORPHS OF BIRDS' EGGS

Fossil eggs have been described a number of times from the Peruvian guano deposits. Raimondi (1856) says that these eggs usually fall in one of two size classes, the smaller and more numerous corresponding to the normal dimensions of the eggs of *Pelecanoides garnotii*, the larger and less numerous to those of *Spheniscus humboldti*. Both these birds burrowed in the guano, so that their eggs are more likely to have become fossilized than those of other species. Pelican eggs have also been frequently identified.

Raimondi (1878) examined a pelican egg from a depth of 1 meter from the surface of the guano of Lobos de Afuera Island and found it to contain a pasty yellow material formed from both yolk and albumen some-

what mixed together. This material had a fetid odor not like that of ordinary rotten eggs but rather resembling a mixture of volatile fatty acids and ammonia. From the same locality an egg from a depth of 3 meters was truly fossilized and massive. The fossilization process therefore takes place in the superficial layers of the guano and cannot be

regarded as providing evidence of great antiquity. It seems possible, from a remark of Gamarra Dulanto (1942), that eggs undergoing replacement by sulphates have been encountered under modern deposits of guano.

Numerous analyses of these eggs have been published and are collected in table 7. Although there are considerable differences in different specimens, it is clear that the main change undergone by the eggs is the replacement of the albumen by potassium and ammonium sulphate, presumably as taylorite, and in some cases by ammonium oxalate also. The shells of the eggs appear from Clark's account to be replaced by calcium phosphate. Wibel points out that the egg that he analyzed contained far more sulphate than could be derived from the fresh egg itself and that an external source of sulphate

must be postulated. As is indicated in the table, three supposed mineral species have been established on the basis of these eggs. Ooguanolite is clearly a mixed potassium ammonium sulphate, though containing more ammonia than typical taylorite. Raimondi believed he had recognized mascagnite in an egg from deep in the Chincha deposit. Guanoxalite, which supposedly approximates to $K_2SO_4 \cdot (NH_4)_2C_2O_4 \cdot 7H_2O$, is obviously a very problematic and by no means necessarily homogeneous substance; the high water content is very curious. Guanovulite is remarkable in being an acid sulphate; Wibel interprets his analysis as $(NH_4)_2SO_4 \cdot 2K_2SO_4 \cdot 3KHSO_4 \cdot 4H_2O$. Acid sulphates very seldom occur in nature, though $KHSO_4$ is known as a rare volcanic mineral, misenite.

TABLE 7

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	%	%	%	%	%	%	%	%	%	%	%	%
H ₂ O	1.00	—	—	6.70	6.30	0.84	3.20	24.80	30.46	9.61	—	(8.85)
Indet. org.	—	—	2.07	—	—	—	tr.	24.50	—	1.11	—	—
Ether-sol. org.	—	—	—	—	27.50	—	—	—	—	—	—	—
Water-sol. indet. org.	—	—	—	2.74	23.15	—	—	—	—	—	—	—
Insol. org.	—	—	—	0.93	16.30	0.83	—	24.50	—	—	—	—
								(alk. sol.)				
Total N	—	—	—	—	—	—	—	2.40	—	—	—	—
K ₂ O	27.93	38.16	2.33	18.61	1.46	35.62	40.13	2.49	21.73	34.75	32.88	5.91
(NH ₄) ₂ O	15.08	11.37	—	18.05	8.43	5.32	6.58	—	12.41	5.29	5.72	29.09
Na ₂ O	—	0.35	—	4.56	0.41	7.85	3.49	0.55	—	—	10.42	5.87
CaO	1.71	—	42.22	0.85	2.13	0.30	—	4.45	—	—	—	—
MgO	0.50	—	—	—	—	—	—	—	—	1.33	—	—
P ₂ O ₅	0.58	—	35.60	1.92	4.95	1.20	9.56	3.75	—	—	1.33	4.14
Cl	—	1.22	0.84	0.74	4.69	0.56	0.55	0.85	—	0.58	—	—
SO ₃	47.59	48.52	—	27.04	2.74	47.14	33.91	2.11	18.47	48.43	47.46	8.22
Oxalate (as C ₂ O ₃)	—	—	—	18.05	2.88	—	1.66	—	17.16	—	0.35	37.39
CO ₂	0.97	—	0.91	—	—	—	—	—	—	—	—	—
SiO ₂ , sand, etc.	4.30	—	0.45	—	—	0.15	—	—	—	0.26	0.60	0.53

I. Hayes (1885), ooguanolite (CaCO₃ and Ca soap, 2.20% treated above as CaCO₃).

II. Rose (1862), Chincha Is., 40 ft., egg 80 mm. by 56 mm.

III. Shell of the same.

IV. Clark (1882), supposed *Pelecanus* egg, white.

V. The same, yolk.

VI. Clark (1882), *Pelecanoides* egg, white.

VII. Raimondi (1878), *Spheniscus* egg, white.

VIII. The same, yolk.

IX. Shepard (1870), guanoxalite.

X. Wibel (1874), guanovulite.

XI. *Pelecanoides* egg, A.M.N.H. (pl. 8, fig. 3), mainly taylorite.

XII. Columbia University, labeled guanovulite but mainly oxammite, probably from rather crushed egg 85 by 66 mm., here referred to *Spheniscus* (pl. 8, fig. 2).

ANCIENT NITROGENOUS GUANO ON THE COAST OF THE CHILEAN MAINLAND

Extensive deposits of guano have been discovered along the northern coast of Chile. Prior to the war of 1879–1882, the northern part of the coast on which these deposits were situated was Peruvian, the southern part Bolivian. Since the important guaneras on this coast differ in certain respects from those of the Peruvian localities that have just been discussed, it is convenient to describe them as Chilean, though much of the data relating to them was obtained during the time when they were controlled by Peru. It is not unlikely that guaneras comparable to the smaller Chilean deposits described below occur as far north as Independencia Bay in Peru, where de la Puente (1933) says fossil guano has been discovered.

The Chilean guaneras were found, apparently in the last year or so of the eighteenth century, by a pilot called Reyes who examined the site of the large deposit of the Pabellón de Pica (Rivero, 1827).

The first available comprehensive account of the localities is that of Tschudi (1851) based on the report made by Rivero in 1845. Essentially the same information was published in the articles here referred to Rivero (1852). A much more detailed survey was later undertaken by a Peruvian government commission under Thierry (1874). During the period of about 75 years between discovery of the guaneras and Thierry's report it is probable that little exploitation took place, the more valuable guano of the Chincha, Macabí, and Guañape Islands being so much more easily extracted. Thierry's account is supplemented by a report by Commander W. E. Cookson, R. N., submitted to the Secretary of the Admiralty in 1874. Cookson was with Thierry during part of the latter's study and confirms Thierry's conclusions. Thierry's report, along with that of Cookson and some chemical analyses by Raimondi, was published together under the title of "Guanos de Tarapaca" for the Peruvian government by its legation in Paris. It is probable that other editions exist; the French version, being accessible, has been used. Cookson's report is also available in English (Great Britain, Parliamentary Sessional Papers, 1874b).

In 1877 Duffield visited the localities. His remarks about the accuracy and good faith of his predecessors are vigorous and uncomplimentary. In the case of one series of deposits, at Pabellón de Pica, regarded as the largest of the guaneras by Rivero, Cookson, and Thierry, it is probable that Duffield had better opportunities for study than the earlier investigators. It is, however, reasonably certain that Cookson would not have concurred in the estimates of Thierry if they had been hopelessly unreliable, and it is quite probable from Duffield's general tone that he was as much concerned in denigrating the Peruvian authorities as he supposes other investigators were in overestimating the potential riches of the region. Estimates of the mass of guano in the Chilean guaneras were also published by Peacock (1874); these, however, prove to be identical with those derived from Rivero's measurements as given by Tschudi. It is clear that Peacock is not a reliable authority, though his alleged estimates have entered the literature of Peru through Pas Soldán.

In recent years a very important study has been made by Brügger (1938, 1939a, 1939b). This gives a good deal of new geomorphological and stratigraphic information. The existing guano beds, described by Brügger, are, however, excessively poor compared with the great riches removed from these guaneras in the last century, and though his account is invaluable, it gives an inadequate idea of the original state of the localities. The most recent contribution to the problem of the Chilean guaneras, namely, that of Bird, is an archaeological work primarily devoted to other matters. One of Bird's sites is of extraordinary importance in elucidating the problem presented by these deposits.

Along the part of the Chilean coast in question, a marine terrace is well developed, indicating a previous sea level about 10 meters above the modern level. Brügger refers to this as the principal terrace. Its relation to the terraces of northern Peru and of Patagonia is not clear. The principal terrace, if it is a single geomorphological entity, appears to have suffered considerable local disturbance. It is believed by Brügger to con-

stitute the elevated plateau of the Mejillones Peninsula, and if this conclusion is correct, a part of the terrace has here been elevated, with little or no tilting, to a height of about 500 meters above sea level. The age of the terrace is problematical. The evidence given by Bird (1943) and summarized below suggests that it is post-glacial, in which case it can hardly be accounted for by eustatic changes in sea level and must represent emergence of a part of the South American continent. The general occurrence of recent earth movements in the Cordilleran region has, of course, long been recognized.

In the majority of cases, the guano deposits of this region are associated with rocky hills which must once have been islands but which now rise out of the terrace just discussed. More rarely the deposits are similarly associated with rocky headlands, too high to have been cut off from the mainland coast. The guano usually fills wave-cut caletones, or gullies, on the sides of these hills, but may form a wide mantle over the lower slopes and between the rocks. There are, however, a few cases in which guano lies on the 10-meter terrace apparently unassociated with any former islands or promontory.

In the old accounts of Rivero (1852) and of Tschudi, the guano deposits known to them are described as having a covering of caliche. This material, which is presumably the same as the costra mentioned by Brügger, has apparently not been analyzed. Rivero speaks of a mechanically formed crust 4 to 6 inches thick, or caliche composed of salt and sand up to 3 or 4 feet thick. Writing apparently of both Huanillos and Punta de Lobos, Cookson says that there are two kinds of crust, one seemingly petrified guano, smelling of ammonia, the other kind apparently formed of a mixture of salt and mud baked by the sun. Both Cookson and Thierry refer to stones and sand lying over the guano. Tschudi indicates that at least in the guanera of Pabillón de Pica, the northern part of the deposit was covered with sand. Duffield speaks of large quantities of sand and stones lying over the guano; these he attributes to relatively recent earthquakes. It is reasonably certain, however, that Duffield's account is exaggerated.

Rivero also speaks of some deposits being covered with alluvial material 1 to 3 varas

(i.e., about 80 cm. to 2.5 m.) thick containing fossil marine shells, and indicates that another bed of guano covered with sand may be above these marine sediments. He supposed that the latter were due either to the Biblical Deluge or to some partial flood or disturbance.

The detailed modern account of Brügger indicates a rather general occurrence of an overburden of crust, rock debris, or sand. Whatever its nature, this overburden argues against deposition occurring in very recent times, and it is clear from Brügger's account that the oldest part of the Chilean guano must have been derived from bird colonies that occupied the abundant islands existing prior to the elevation implied by the terrace. Some guano was, however, apparently being formed at Pabellón de Pica, as well as on the limited number of Chilean guano islands already discussed, during the nineteenth century.

In addition to the deposits considered in detail below, two other classes of guanera are known on the Chilean mainland. These classes are more conveniently discussed separately. The first contains the guaneras of the Mejillones Peninsula, which in their genesis are comparable to those to be discussed in this section but which have undergone an immense uplift. This has resulted in the deposits' being exposed to more humid conditions due to the coastal mist or garua that condenses most vigorously around elevated peaks. There has therefore been much more decomposition and leaching of the organic and soluble components of the Mejillones guano than elsewhere. The second class (p. 112) of guaneras on the Chilean mainland contains certain curious but inadequately known deposits in the Atacama Desert which, though rich in organic matter, differ chemically from coastal guano and may well be partly of mammalian origin.

DESCRIPTION OF THE COASTAL CHILEAN GUANERAS

MAINLAND DEPOSIT NORTH OF PISAGUA

Fallon (1899) describes a deposit of 2000 tons north of Pisagua, which he states was termed no. 13 and was commercially valueless. He gives an analysis of the best part of

this deposit, which was apparently almost one-fourth sodium chloride. In another part of the deposit, he made a detailed section as follows:

- 60 cm. conglomerate of sand and pebbles
- 20 cm. pebbles and sand
- 40 cm. guano, sand, shells, and pebbles
- 10 cm. shells and sand
- 100 cm. very sandy guano mixed with stones and shells
- 60 cm. sand, stones, and pebbles
- 40 cm. sand, stones, and fragments of rushes used for matting

The entry about the rushes may conceivably indicate an archaeological site, but it is more probably intended merely as a descriptive epithet of the plant in question. The profile, however, does suggest slight marine transgression after the deposition of the guano.

PUNTA PICHALO

LATITUDE 19° 37' S., LONGITUDE 70° 15' W.

The site of a deposit of old guano of extraordinary importance on account of the ar-

chaeological investigations of Bird (1943), whose description is the basis of the following summary (fig. 22).

The locality is on a sharp, low, rocky promontory which runs out from the coast south of the town of Pisagua. This promontory is washed by the sea, and no beach is developed. At about 10 meters above the present high-tide level, a shore line is said to be cut in the promontory; this shore line is marked by a low and steep cliff. There is a level area between small rock bosses at about 30 meters on the northern side of the tip of the promontory. This level area is the site of a midden 4 to 5 meters thick, which lies over a deposit of "cement-hard sand, dirt and stone fragments" and beneath this, compact reddish "fossil" guano mixed with stones. The midden area lying between rocks is evidently comparable to the depressions between small rocky mounds in which guano has been found in other Chilean localities. No unequivocal evidence of the association of artifacts with the guano layer was found. A purely visual estimate indicated that the

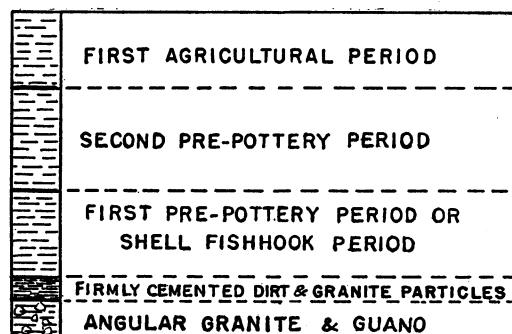
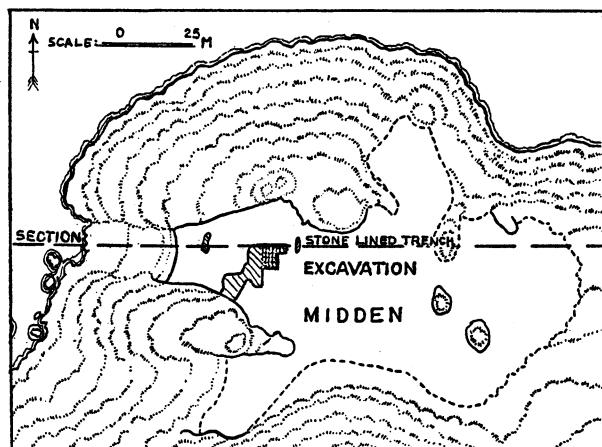
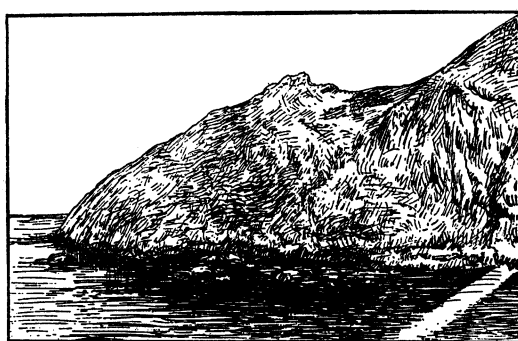
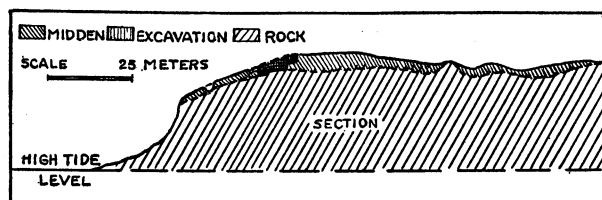


FIG. 22. Topography, general aspect, and stratification of the archaeological site at Punta Pichalo. Modified after Bird.

quantity of disintegrating rock present beneath unit area of the surface of the midden is several times the amount of rock debris per unit area in the sterile layer between the midden and the guano. The guano deposit, which presumably was formed by a bird colony on the promontory when the sea stood at a higher level, is therefore apparently separated in time from the lower occupational level by a period only a fraction of the time taken to accumulate the midden. The midden itself has yielded the remains of four superimposed cultures. The older two, but not the later two, lack pottery, coiled basketry, and agriculture. They therefore probably antedate the oldest cultures of Peru. The lowest culture, designated by Bird as the shell fish-

cliff base at 10 meters. Bird thinks that the relationship of the guano to the present sea level suggests uplift of the order of 10 to 15 meters since the fossil guano was deposited. He points out that some guano is deposited at a lower level, near the water, at the present time.

PUNTA GRUESA

LATITUDE 20° 23' S., LONGITUDE 70° 13' W.

This is the Punta Grande of Tschudi and is the foot of the high Morro de Tarapacá. The occurrence of guano in this locality is described by Brügger (1938). There are a number of small hills projecting from the principal terrace that lies between the moun-

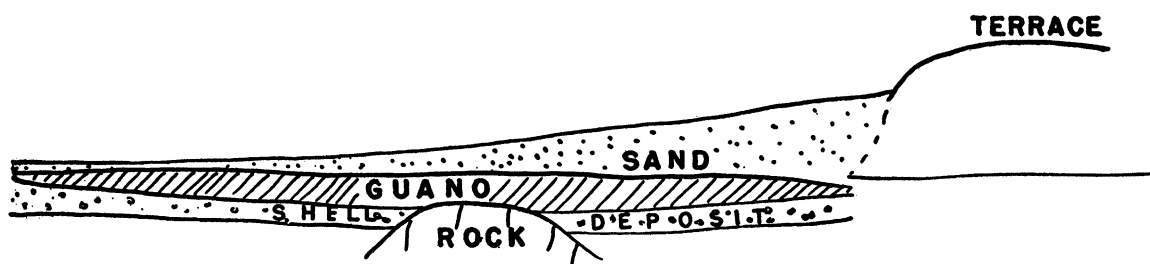


FIG. 23. Diagrammatic section through the guanera at El Toyo. After Brügger.

hook culture, also occurs at sites near Aricá, to the north of Punta Pichalo. At one of these sites, Quiani, a sterile layer of 20 cm. of sand and rock debris that has fallen from the hillside above lies under the lowest culture layer which belongs to the shell fish-hook culture. This 20-centimeter layer corresponds to considerably less material from the same source than has accumulated in the occupation levels. Immediately below the sterile debris is a layer of clean beach sand 15 to 16 meters above high water. At Playa Miller, Aricá, the shell fish-hook culture occurs at the bottom of a midden lying directly on clean beach sand 1.58 meters above high tide. These observations can only mean that emergence of the order of 10 to 15 meters took place at a time that is not very much more remote than the beginning of the shell fish-hook culture, and was still continuing before that culture ended. This chronology supports the view that the guano deposits on Punta Pichalo were formed at a time when the sea level stood higher than it does today, probably at the

tain and the sea. In the southern part of these hills, guano was dug during the nineteenth century. The deposits were covered with sand containing much shell debris. There were wide gullies, which in one case ended in a large cave, and these were filled with guano covered with rock debris. Brügger indicates that the cave was cut at 20 meters, and his diagram indicates guano filling the gully to sea level. Tschudi lists seven deposits, named Lobos, Culaca, Sacramento, Animas, Morillo, Guajes, and Colorado. He states that a thick caliche layer covered the guano and that there was a good quantity of sand over the deposits. Such guano gave rise to the belief that the material was of mineral origin. Some of the guaneras were probably exploited in Incaic times, and most of the material dug in the last century was apparently used locally. Red and gray guano predominated. Though the general occurrence at Punta Gruesa is clearly similar to that elsewhere, the relationship of the guano deposit to uplift is uncertain.

EL TOYO

A rather exceptional guanera apparently exists between Punta Gruesa and the next localities, at a place called El Toyo. Here the deposit is unassociated with any island or headland and lies on the principal terrace. It forms a layer from 0.6 to 2.5 meters thick, thinning out towards the sea, lying on a shell deposit and covered with sand (fig. 23). At the landward edge of the deposit, another terrace rises. This terrace is formed of angular fragments from the surrounding desert mixed with clay. It is uncertain, to Brügger, whether it is antecedent to the lower main terrace or represents a mud-flow over the latter. Brügger suggests that the bird colony occupied a sheltered part of the upper terrace while the lower terrace formed the beach. Occasional waves may have washed guano down from the bird colony onto the flat beach below. This explanation seems very improbable. The guano is said by Brügger to contain 2.6% to 3.0% N and 14% to 15% P_2O_5 .

CHUCUMATA

LATITUDE $20^{\circ} 34' S.$, LONGITUDE $70^{\circ} 13' W.$

This and the neighboring localities of Payta and La Guaija have guaneras lying in caletones and between small rocky hills, which at least in the case of the first-named rise from a part of the terrace. Detienne (1880) says that the coast at Chucumata has guano spread out over the plain in a uniform but poor layer that has lost its nitrogen. This is attributed to the action of the sea washing deposits on the hills down onto the plain during a marine transgression determined by local earth movements. At a guanera called Chucumata 13 there appears to be a thin guano mantle around the larger hills, in continuity with the deposit in the richer gullies.

SAN PEDRO

A newly exploited guanera just to the south of Chucumata. Brügger's photograph and description indicate that the guano under exploitation lies in a gully on the side of a

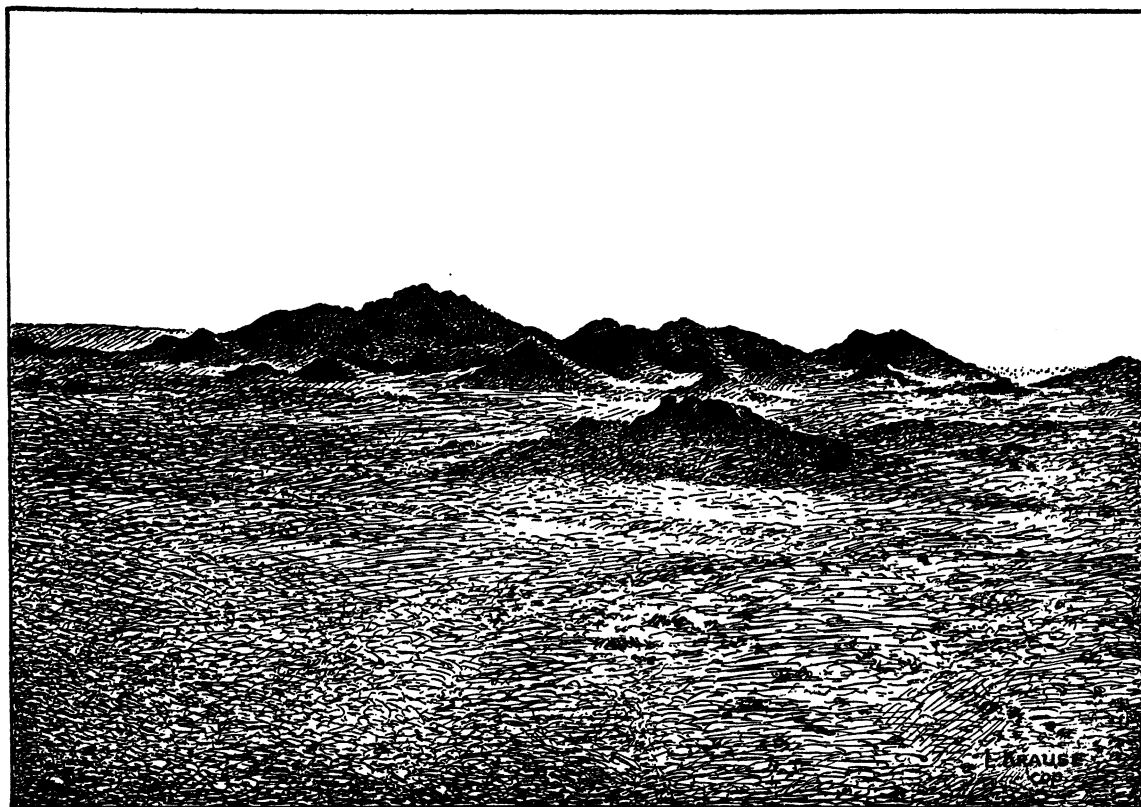


FIG. 24. Ancient islets at Patillos. Redrawn from Brügger.

small hill rising from the coastal terrace. It is said to contain 3.40% N, while the camotillo contains up to 6.40%. The guano layer is 2.5 meters thick under a sandy crust with loose sand 1 meter thick.

PATILLOS

LATITUDE 20° 47' S., LONGITUDE 70° 14' W.

A group of low, irregular, rocky hills lies south of the port of this name, rising from the coastal terrace. Various trial pits indicated that between some of these hills there is a guano layer 20 to over 40 cm. thick, the overburden on the 20-cm. layer being described as 30 cm. of sand and crust, though at other points up to 3 or 4 meters of sand appear to cover the caletones filled with guano. Brügger's photograph of this locality, from which figure 24 is prepared, shows diagrammatically the typical landscape presented by the guaneras of this region, in which the ancient islets rise from the main terrace. Thierry states that there was a small deposit 3 miles north of Patillos. He gives the total reserve for Patillos as 1500 m³ at most, but this appears to include modern guano deposited on Patillos Island.

DIQUE

A locality 5 kilometers south of Patillos. The guaneras consist of small hills, with some superficial deposits of guano poor in nitrogen. One trial pit indicated 20 cm. of sand beneath which was a crust covering 80 cm. of guano (Brügger, 1938).

PATACHE

LATITUDE 20° 50' S., LONGITUDE 70° 13' W.

The site of a series of small hills, decreasing in elevation in a seaward direction and lying below a high headland. These hills rise out of the principal terrace and must have formed a series of islands off a rocky promontory when the terrace was submerged. Brügger indicates that guano occurred here chiefly in caletones cut in these low hills. Thierry gives two maps, of which the first probably represents the area discussed by Brügger, but which show considerable but possibly exaggerated guano filling between the low hills. Brügger states that two groups of guano-filled caletones existed, one to the west of the

third hill below the headland, and the other farther east. These may be represented by guano-bearing areas on Thierry's map, but no certain identification is possible. A diagram given by Brügger of an almost worked-out caleton in the first group is here reproduced (fig. 25), showing the guano thinning out in two strata under an overburden of debris, at the base of the hill. Brügger states that the guano at Patache began at an alti-

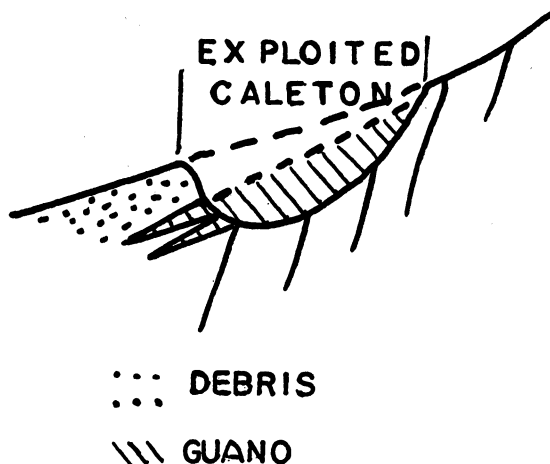


FIG. 25. Diagrammatic section through an almost exhausted caleton at Patache. After Brügger.

tude of 40 meters above sea level. This presumably refers to the top of a caleton filling. A small deposit under a crust 30 to 50 cm. thick associated with very low hills is said by Brügger to have lain on the terrace in cracks in the granite. This yielded 10,000 tons and may be the guanera indicated in Thierry's second map. The total reserve at Patache was supposed by Thierry to have been 125,000 m³ in 1874.

CHANAVAYA

LATITUDE 20° 56' S., LONGITUDE 76° 11' W.

A locality formerly called Puerto Ingles, the site of an important group of guaneras worked before the Chileo-Peruvian war. The guano occurred in caletones and between rocks on ancient islands now united to the mainland. A plan of the deposits given by Tschudi (1851) and a better map by Thierry indicate a large area of guano on the southern side of a peninsula bearing a number of small hills. Tschudi states that the neck connecting this

peninsula with the mainland is strewn with recent shells. He indicates that the depth of the guano varied between 18 and 25 varas, i.e., 15 to 21 meters. These observations tend to cast doubt on the statement made by Brügger that the guano did not extend higher than 10 meters above sea level. Rivero estimated the volume of the guano as 2,585,000 cubic varas, i.e., 1,524,000 m³. The corre-

Rivero's figure (i.e., Pas Soldán after Peacock). It is virtually certain that the estimate obtained by Rivero and published by Tschudi is excessive on account of an overestimate of the mean depth.

PABELLÓN DE PICA

LATITUDE 20° 56' S., LONGITUDE 70° 11' W.

The site of one of the most important de-

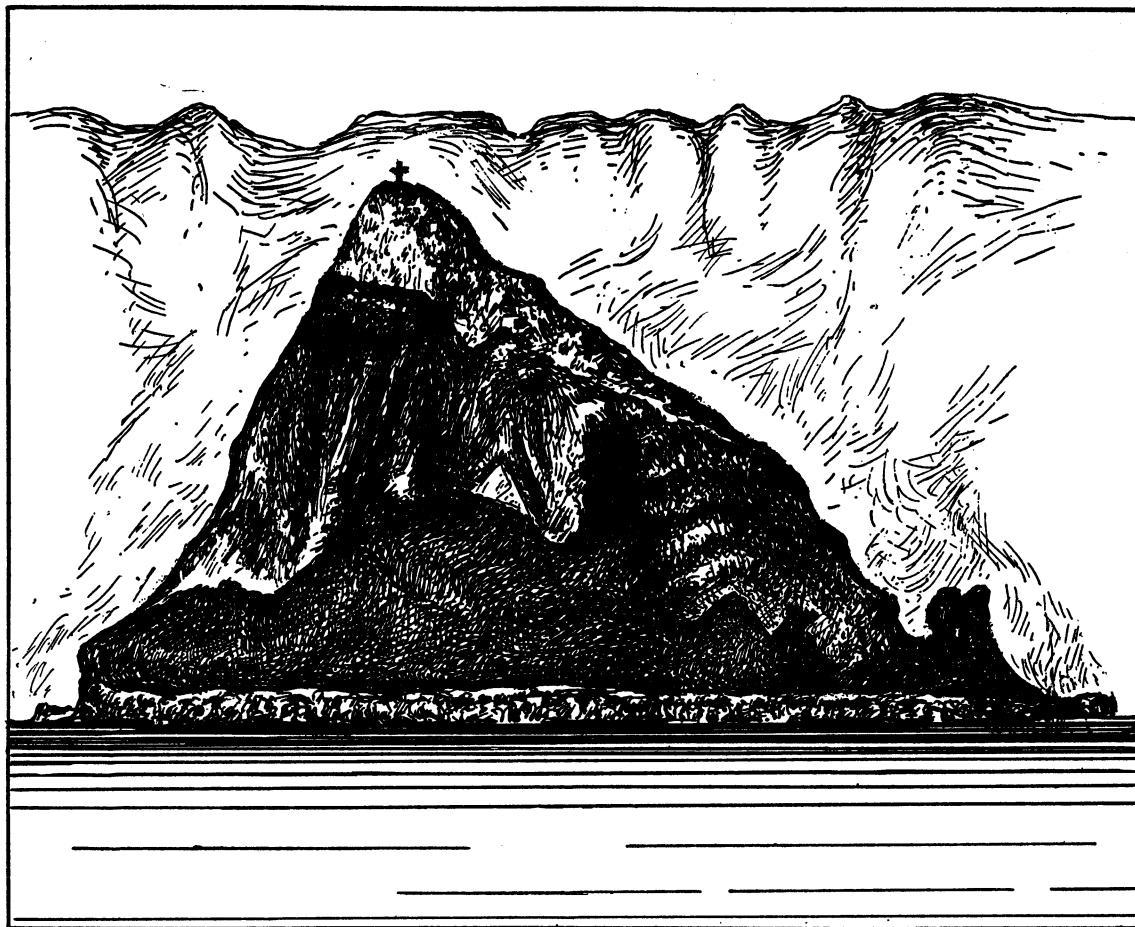


FIG. 26. Pabellón de Pica. The darkest area at the bottom represents the part of the guanera exploited before the drawing was made. After Thierry.

sponding mass is given as 1,292,500 tons, a value that is repeated by Peacock. Thierry gives no details other than a map. He takes the mean depth as 5 meters and the volume as 287,500 m³, of which 137,500 had already been removed, leaving 150,000 m³ to be exploited. This last figure is quoted by Brügger from Vidal Gormaz as more reliable than

posits on the Chilean coast. The guaneras lay at the foot of a headland 318 meters high connected to the coastal Cordillera by a high neck that lies well above the guano deposits. The high headland, therefore, cannot have been an island when the bird colony was depositing the guano. The marine terrace is poorly developed, but Brügger's photograph

seems to indicate a raised strand line at the tip of the promontory and perhaps partly covered with debris on its north side. Thierry's sketch also shows this raised beach or terrace (fig. 26). Brügger's description and photographs indicate that on the western side of the headland it is dissected by caletones or narrow gullies which are often continued down to sea level where they are being deepened by contemporary wave action. These gullies reach 100 or 150 meters up the side of the headland. The guano of the western slope lay in these caletones, which appeared as slight superficial depressions covered with rock debris. The guano was distinguished from the overburden by its lighter color and more regular stratification, parallel with the slope of the mountain. Cookson and Thierry indicate that the main ravines were named from north to south, Cueva, Guardian, San Lorenz, Infiernillo, Barlovento, Tigre, and Rinconada.

Duffield states that there were 18 such ravines filled with guano. These ravines he compares to the spaces between a nineteen-fingered hand with an immensely broad palm. Tschudi (1851) gives a map of the locality, apparently made by Rivero, which shows a continuous but irregular strip of guano along about 1.4 kilometers of coast, presumably at the foot of the Morro. The inner margin of this strip is very uneven and apparently corresponds to at least nine caletones and probably more. Only the extreme northern part is indicated as being covered with sand.

Cookson says that the slopes of the guano, evidently covering a considerable part of the lower sides of the mountain, were scattered with rock debris and that the ravine known as Tigre had a cover of sand. The guano was also said to contain rock debris in small quantity. Thierry says that in places yellow guano was exposed and that in other places there was a white oxidized surface layer. In yet other parts of the deposit, the guano was overlain by sand and stones. It is hard to reconcile Cookson's statement with the indication of sand only in the northern caleton in Tschudi's map. Duffield's remark that the whole deposit was covered with 50 feet of sand and stones, cleared before he visited it, is an obvious exaggeration. It is quite possible that the labor of removing the

sand prior to Duffield's visit was exaggerated in the accounts that he received, possibly to justify excessive expenditure.

In addition to these deposits, Brügger indicates that on the southern slope of the mountain a large amount of debris lies against a fault scarp, and that guano beds are interstratified in the debris. Brügger's diagram of the occurrence is here reproduced (fig. 27).

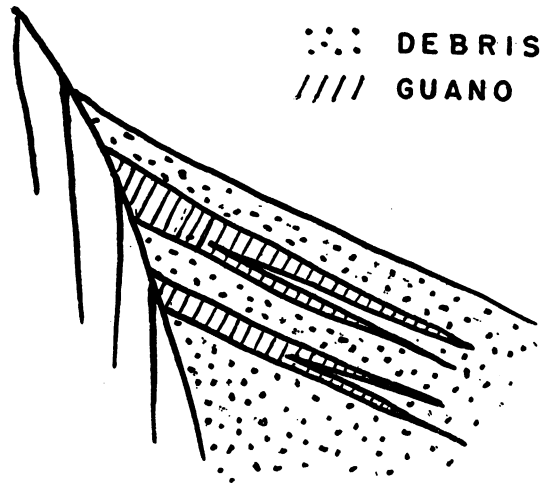


FIG. 27. Section through debris lying against the fault scarp on the southern side of Pabellón de Pica. After Brügger.

The purer part of the guano layers lay against the rock face, and the beds thinned out away from the mountain and also eastward, inland. Similar deposits apparently lay on the less accessible northern side of the Morro. As has been previously indicated, Cookson was informed that about 1834 the whole promontory was alive with birds, but that after about 1848, when a mass mortality occurred, the colony disappeared, while Carrey (1875) writing in 1875 also records this mass mortality as having occurred about 30 years before. The white guano analyzed by Voelcker (1874) from the caleton Barlovento was doubtless produced by the colony reported to Cookson, but how continuous guano production had been at Pabellón de Pica in previous centuries it is impossible to ascertain. Using the data given him by Hindle (p. 21) and his own estimate of the mass of guano, Cookson concluded that it would take but 300 years to produce the deposit of Pabellón de Pica.

The guano of the main series of caletones is said by Tschudi to have varied much in color, generally being reddish or gray, but with a dirty white layer in the middle of the deposit. The deposit was stratified, the strata being horizontal, contrary to what Brügger says, except up against the mountain, where they were inclined upwards. Tschudi's remarks about stratification are doubtless based on cross sections of deposits. The depth was variable; in some parts of the guanera a mean depth of 40 varas, i.e., 33.5 meters, occurred. The greatest depths were said to be in the "Quebradas der Mitte und des Rückens" which is ambiguous. In the northern part of the deposit, a ravine was filled with 35 to 40 varas of guano with a heavy cover of sand, but elsewhere his map does not indicate a sand covering. The total area is given as 240,801 square varas and the volume as 5,950,000 cubic varas, corresponding to a mean thickness of 24.7 varas, or 20.7 meters, and a volume of 3,510,000 m³. The corresponding mass is given as 2,795,000 tons. Considerable exploitation had already taken place when Tschudi wrote.

Thierry estimated the volume as 5,000,000 m³. Cookson thought 4,500,000 tons a more accurate estimate than Thierry's, but he apparently was under a misconception that Thierry's value was in tons and was based on a density of 1.33 instead of 1, which he felt a truer value. Thierry considered the mean depth to be 20 meters.

Duffield states that in 1876, up to 8,000,000 tons of guano were reported and that official estimates of 5,000,000 and 3,510,640 tons had been made, apparently prior to removal of the overburden. The first official estimate is obviously that of Thierry. Duffield adds that another unofficial and disinterested group put the amount at less than 1,000,000 tons and that he himself concluded after measurement that there may have been 1,000,000 tons present early in 1877. Thierry's map is admittedly provisional and not detailed, but although Duffield saw the locality when much overburden present in 1874 had apparently been removed, his strictures on the official estimations are probably unfair. He gives no indication of how he did his survey, merely indicating how much he disliked the locality. It seems not unlikely

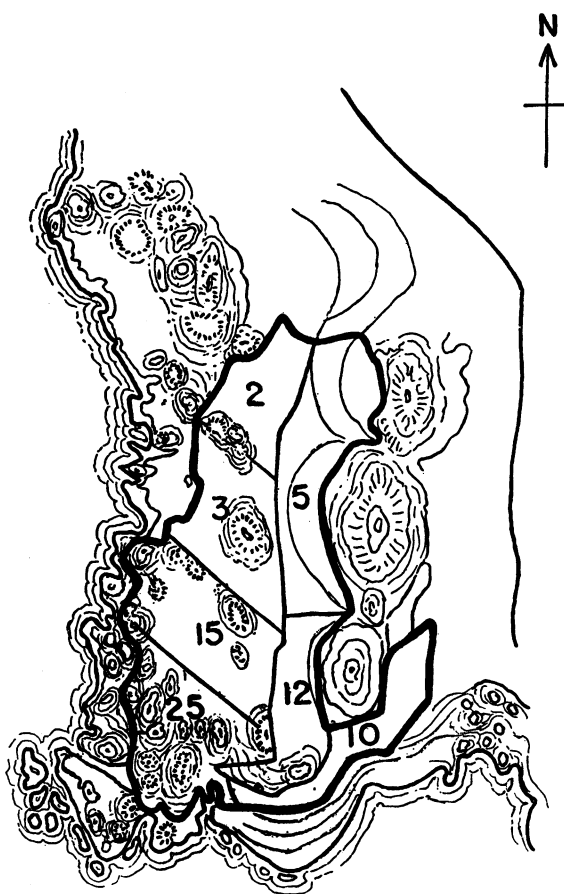


FIG. 28. Punta de Lobos, map of the guanera. Numerals indicate mean depths in meters of the areas into which the guanera is divided. After Thierry.

therefore that his estimate is not so reliable as he claimed.

PUNTA DE LOBOS

LATITUDE 21° 05' S., LONGITUDE 70° 12' W.

A promontory bearing a number of rocky hills of granite and micaceous schist. Thierry's map here reproduced (fig. 28) indicates four elliptical hills set in a row parallel with, and about 300 meters from, the coast, and a very large number of small mounds nearer the sea. The main guanera lay between the four larger hills and the small mounds but filled also most of the depressions between the more southern of the latter. Guano filling caletones in the slopes of the mountains inland from the rocky elevated islands also occurred.

On the southeastern side of the small bay,

enclosed by the southern shore of the point, another deposit existed, filling two depressions. Tschudi indicates that in both cases the guano reached to sea level, a fact confirmed by Brügger for the smaller southern guanera, and probably also shown by the position of several exploited depressions in the southern part of the main guanera indicated on Thierry's map. Although it is probable that the mounds, when islands, supported bird colonies, it is obvious from the distribution given on this map that a great deal of guano must have been deposited at a time when the depressions between the mounds were already dry.

According to Tschudi, there was a caliche crust 15 to 60 cm. thick over the guano. Cookson's observations on the crust, quoted above, were apparently partly based on the condition at Punta de Lobos. Cookson figures a profile probably from the southern part of the guanera, showing several feet of guano lying above a layer of rock debris several inches thick, which in turn covered more than 100 feet of guano. In the middle of this lower layer, there is an immense boulder. Brügger indicates that he examined one of the remaining guano layers at Punta de Lobos, finding that it lay under 5 meters of debris.

Tschudi gives the depth of the main deposit as varying between 12 and more than 22 varas, i.e., from 10 to over 18.4 meters. The small southern deposit had a depth of 16.7 to 21.0 meters. The usual depth according to Tschudi was 13.4 to 16.7 meters, but for a mean depth he, or rather Rivero, used 21.1 varas, or 17.7 meters.

The area of the guano deposit on Thierry's map is divided into a number of sections, and for areas defined by grouping these sections, the estimated mean depth is given. In the redrawn version of the map here given (fig. 28) these areas have been indicated, and the mean depth is entered for each area. The stratification is said to have been horizontal or slightly sinuous. The guano was light reddish in the upper layers, gray or plumbeous in the lower. Rarely, blackish material was present and was shown by the presence of remains of skin, bones, and stomach stones to be derived from sea lion feces. This sea lion guano apparently formed a layer about 50 cm. thick in the middle of the

deposit, lying over gray and yellowish layers. The stomach stones were smooth elliptical fragments of porphyry about 5 to 7.5 cm. long (Tschudi, 1851).

According to Tschudi, Rivero estimated that the total volume was 2,921,580 cubic varas, corresponding to 1,723,000 m³. The corresponding mass given is 1,460,750. Thierry gives a total volume of 1,696,890 m³ in his detailed table, 1,601,000 m³ in an abbreviated table, and 1,701,153 m³ in the text. The first figure is probably the correct one. He considers that it is prudent to allow not more than 1 ton per cubic meter. Cookson, however, gives 2,000,000 tons. Duffield remarks of Thierry's figure, 1,601,000, that "utmost carelessness must have been observed" in obtaining the estimate and that the true reserve in 1877 was 2,500,000. It is at any rate certain that the original reserve was of the order of magnitude of 2,000,000 tons.

Raimondi (1878) records a mummy of a young pelican, supposedly not the same as that now living on the coast, and of a cormorant, supposedly *P. gaimardi*, both from under 3 meters of guano. The significance of these records is very dubious.

According to Brügger two groups of small hills known as La Guara N and La Guara S, situated a few kilometers south of Punta de Lobos, have caletones which may contain guano; there is much wind-blown sand, and evidently trial pits did not disclose significant deposits.

PUNTA CHOMACHE

LATITUDE 21° 11' S., LONGITUDE 70° 10' W.

Formed by a group of small hills and headlands. Considerable deposits of fresh guano derived from *Phalacrocorax bougainvillei* have already been considered. On the northern slope of the north headland or morro a deposit of reddish guano, containing 10.53% P₂O₅ and 0.42% N was discovered under 10 cm. of sand and debris. Patches of sandy reddish guano were noticed elsewhere.

HUANILLOS

LATITUDE 21° 16' S., LONGITUDE 70° 08' W.

With Pabellón de Pica and Punta de Lobos, one of the three most important guaneras ex-

ploited on the Chilean coast during the last century. The locality appears to be a headland on the western slopes of which an extensive mantle of guano, as well as guano filling in caletones, occurred. This guano appears to have been covered by a crust which Tschudi states was impregnated with salts. On the southern slope the guano lay, according to Brügger, under a layer of debris, dipping from the rock face of the headland and thinning out into the debris, while on the northern slope the guano formed a uniform mantle under a layer of debris. On the western slope, Brügger specifically indicates that the guano descended to 20 meters above sea level, and on the northern slope the mantle is shown as descending to a terrace at 20 meters above sea level. The debris over the surface was apparently very coarse and in places 4 meters thick. Thierry indicates that the main deposit lay in four depressions running up the hillside to 100 meters above sea level. He observed depths of up to 25 meters, though only one of the areas into which he divided the deposit is given as having a depth as great as 9.33 meters. The mean depth derived from his calculations was only 5.8 meters.

According to Tschudi, whose map indicates four imperfectly separated areas, probably representing the deposits of the western part of the promontory, there was a bird colony consisting of the skimmer, *Rynchops nigra* Linnaeus, which he calls the piquero, *Pelecanus o. thagus*, and *Larus modestus*, producing white guano in the upper part of the central guano-filled ravine. Duffield indicates five gorges or caletones and states that in places rocks weighing over 1000 tons lay on the deposit, apparently as the result of earthquakes.

Tschudi indicates that the total area of the deposit was 158,242 square varas and the volume 3,825,000 cubic varas, corresponding to a mean thickness of 24 varas, or 20.1 meters, and a volume of 2,315,000 m³. The equivalent mass is given as 1,912,500 tons. Since the middle and northern ravines are said to have had the most important deposits, 15 to 20 varas thick, it is obvious that this mean thickness is exaggerated. Thierry (1874) concluded 700,000 tons and Duffield 800,000 tons to be present in the 1870's.

A group of small hills dissected by large caletones lying to the north of the main deposit was investigated by Brügger. In one ravine he found:

Superficial sand	20 cm.
Impure guano with 2% P ₂ O ₅ and indications of nitrogen	30 cm.
Hard crust of sand cemented with salt	20 cm.
Impure guano	20 cm.
Very hard crust indurated with salt	5 cm.
Crusts about 2-5 cm. alternating with sand*	70 cm.
Shelly fragments	4 m.

* "Alternacion de costras parecidas de 2 a 5 cm. con arena de guano [*sic*] grueso," perhaps a misprint for "grano grueso."

PUNTA BLANCA

A few kilometers south of Huanillos; has a group of small hills, some of which bear caletones containing guano, while some sandy yellow guano is found in depressions between them. At least part of the deposit lay beneath a sterile overburden. The eastern slope of a hill called Jote has a large caletón from which 1120 metric tons of guano have been recovered. Brügger indicates the existence of white guano containing 22.95% P₂O₅ but only 0.94% N in this locality.

PUNTA FALSA DE CHIPANA

LATITUDE 21° 23' S., LONGITUDE 70° 07' W.

The site of a guanera which lay on the coastal terrace unassociated with any rocky hills or former islets, and of considerable importance in the last century. The terrace is broad and well developed in this part of the coast; from Tschudi's account the guano deposits appear to lie upon it at an altitude of 21 to 25 meters (i.e., "25-30 Ellen = varas") above sea level, while Thierry gives the altitude as 35 meters. The deposit was covered with a thin layer of sand, below which a thick and hard crust lay over the guano. This was in general up to 50 cm. thick and is described as "saltpetre" by Thierry; for the peripheral part of the deposit it was apparently thicker and more saline. The material of this crust had been apparently sought by the inhabitants of the region, either as a source of salt or for fertilizer. The guano beneath it in the

center of the deposit had also been worked by sinking shafts and then tunneling beneath the crust. Some of the guano is said to have been very hard and rock-like, though containing up to 7% N (Fallon, 1899). The high chloride content is noted by Detienne (1880), and Brügger states that much of the guano contains 12% to 15% NaCl.

According to Brügger a layer of guano 2 meters thick still existed in places in the central part of the guanera when he examined it, and below this was a second thin crust which in places lay over a guano layer 10 to 20 cm. thick, occupying depressions in the bed rock. He also states that west of the main deposit guano rich in salt is covered with shell, and lies over powdery guano poor in nitrogen. It appears therefore that the deposit at Chipana has had a complex history and that in all probability some marine transgression has taken place since it was formed.

Tschudi, on the basis of Rivero's investigation, thought the deposit was about 10 meters thick; this is certainly an exaggerated estimate. Thierry made a more complete study, dividing the area of the guanera into 12 sections which varied in depth from 0.20 to 4.00 meters. Unfortunately the map accompanying his report does not give the position of these sections. Thierry's account of the computation of the original reserve is confused, as the material estimated as lying between the tunnels appears to be allowed for twice in the calculation, and the results are differently presented in the text and tables. Taking his estimate of the area worked at 15,735 m² with a mean depth of 1 meter, the quantity in this area would be 15,735 m³ which apparently includes 6290 m³ between the tunnels. The untouched area of 41,228 m² is estimated as containing 67,422 m³. The original reserve therefore seems to have been 83,157 m³.

Brügger indicates that on the east of the camp at this guanera lies another deposit named Rinconada associated with elevations rising out of the coastal terrace. The guano deposit, about 1 meter thick, was used as a cemetery by the ancient inhabitants of the region, but no data on the archaeology are forthcoming. A detailed section gave:

	CENTI- METERS
Dark pebbles from surface with shell fragments	20
Yellow guano said to contain 0.5% N	10-30
Dark pebbles and sand with shell fragments	30
Angular rock fragments 10-15 cm. in diameter	30
Guano with 1% N	25-50
Dark sand with little shelly material	10-15
Guano	15
Dark sand above with large choro shells	

GUANERAS SOUTH OF THE MOUTH OF THE RIVER LOA

Brügger mentions four localities between the mouth of the River Loa and Mejillones Bay, namely, Huachan, Lautaro, Punta Arenas, and Paquica. No details are given and the deposits are doubtless unimportant, though the last-named guano is presumably that mentioned by Rivero (1827) as Punta de Paquica. Brügger investigated other favorable localities in this region but without success.

CHEMISTRY OF ANCIENT CHILEAN GUANOS

Though it is not quite impossible that the saline guano analyzed by Denham Smith came from one of the Chilean guaneras such as Huanillos, the only fairly complete analysis of a material certainly to be attributed to this part of the South American coast is that of Raimondi (1878) for Chanavaya. Raimondi's analysis given above (table 5) is published along with analyses of guanos from the Chincha Islands and Guañape.

The Chanavaya guano was regarded by Raimondi as exemplifying accumulation under the driest conditions known on the guano coast, while the Guañape guano exemplified material from the least arid region in which nitrogenous guano accumulates. The Chincha Islands occupied an intermediate position both geographically and meteorologically. Though the quantity of uric acid in Raimondi's Chanavaya sample is actually greater than the amount that he records in the other two specimens, and the amount of oxalic acid slightly less, both substances are present in all Raimondi's samples in much smaller amounts than are recorded by Karmrodt in

Chincha Island guano. In general, apart from the slightly greater amount of uric acid and correspondingly lesser amount of ammonia, there is little difference in composition between the Chanavaya and Chincha Island guanos analyzed by Raimondi, and in view of the possibility of technical defects in the analyses it is not possible to establish any significant differences between the Chincha and Chanavaya specimens.

A number of less detailed analyses, by Voelcker and by Raimondi, also exist. These analyses, with one of a poor saline guano from north of Pisagua (Fallon, 1899), are presented in tables 8 and 9. If the three main guaneras of Pabellón de Pica, Punta de Lobos, and Huanillos examined by both Voelcker and Raimondi be considered, it is evident that there are certain striking differences in the results of the two investigators. Raimondi records a significant amount of CaCO_3 and other inert matter, as well as alkaline salts and sand, which might be regarded as inert from the standpoint of the fertilizer trade. Voelcker has no such category. If his category "alkaline salts" covers both the alkaline salts and the CaCO_3 and other inert matter of Raimondi, then the alkaline salts of the latter investigator tend to be rather high. Raimondi records an extraordinary amount of soluble P_2O_5 in his analyses and comments on its presence in his text. On the other hand many of his nitrogen determinations are low. It is possible that Raimondi's nitrogen figures, which are recorded as ammonia, refer only to ammonium salts and not to total nitrogen. This, however, is unlikely, for where the organic matter is as high as in Pabellón de Pica III ($\text{N}=11.73\%$) and Punta de Lobos III ($\text{N}=12.9\%$), the nitrogen constitutes, respectively, 24.7% and 21.4% of the organic matter and ammonia salts, which is a not unreasonable figure if total N is implied but is very high if only the ammonia nitrogen is recorded.

Part of the difference between Raimondi's and Voelcker's analyses is due to the fact that the very diversified analyses of the former were based largely on samples taken during a survey, while Voelcker had more uniform material, presumably of known commercial value. It is also not impossible that some change in transport to England is involved in

explaining the differences. It is, however, quite likely that Raimondi was not able to use such good analytical methods in Peru as were available to Voelcker and that the latter's analyses, though selected samples, give a more reliable picture of the chemistry of the Chilean guaneras.

In figure 29 the nitrogen and phosphorus contents on a moisture-free and sand-free basis of all these analyses have been plotted in the same way as in figures 20 and 21. It will be at once observed that there is a marked tendency for the points to fall far below the regression line derived from fresh guanos, a tendency not observed, save in the case of Independencia Bay guanos, when the data from old insular Peruvian guanos are plotted (fig. 21) in the same manner. The analyses themselves moreover indicate very clearly that this general characteristic of the old Chilean guanos is largely due to the accumulation of alkaline salts, which in part at least must be derived from the sea. This is known to be the case at Huanillos, just as it is at Independencia Bay. It is possible that there is a further contribution to the alkalis that has been derived from desert soils. The crust, as has already been indicated, is known to have contained nitrate, and some calcium carbonate may also be of terrestrial origin. The Chanavaya analysis unfortunately throws little light on the problem. It is, however, reasonable to suppose that during the very long period of existence of these Chilean guanos, slight impregnation by wind-borne salt as well as perhaps capillary enrichment from the debris on which much guano rested took place. The chemistry of the Chilean guanos when compared with the old Peruvian insular guanos is therefore consistent with the hypothesis that the former deposits are as a whole considerably older than the latter. It has already been suggested that apparent differences in the fluorine content point in the same direction. It is also to be noted that the chemical determinations of samples from small guano beds still remaining, given by Brüggén and quoted incidentally in the preceding section, resemble those of Raimondi for the poorer minor localities given in table 9 in their low nitrogen content. Large amounts of nitrogen were probably mainly retained in the most extensive guaneras, where the de-

TABLE 8

	H ₂ O	Organic +NH ₃ salts	P ₂ O ₅ Total	P ₂ O ₅ Sol.	CaO, Re- corded as Ca ₃ P ₂ O ₈	Alka- line Salts*	CaCO ₃ and Inert Matter	Sand	N
PABELLÓN DE PICA									
RAIMONDI:	%	%	%	%	%	%	%	%	%
Main slope	11.00	47.50	13.79	9.30	5.31	12.50	6.60	3.30	7.83
"O. P."	7.50	13.00	15.66	3.20	14.74	27.00	11.10	11.00	0.99
—	12.50	47.50	17.30	10.50	8.20	11.00	0.70	2.80	11.73
Infiernillo	3.70	48.10	12.72	10.20	2.98	16.20	13.80	2.50	9.94
<i>Mean</i>	8.67	39.02	14.87	8.30	7.78	16.67	8.05	4.90	7.62
VOELCKER, 1874:									
La Cueva, 25 ft.	3.20	46.17	13.49	1.81	13.83	13.68	—	9.63	9.81
S. Lorenzo, 15 ft.	5.45	49.40	14.06	1.70	14.64	14.29	—	2.15	9.15
Barlovento, surface, white	4.13	59.01	11.67	1.68	11.83	7.32	—	6.04	15.08
Rinconada, surface	9.23	41.32	11.57	0.67	12.90	22.63	—	2.35	6.68
Rinconada, 50 ft.	6.70	55.10	14.72	3.48	13.32	8.62	—	1.55	11.02
<i>Mean</i>	5.74	50.20	13.10	1.87	13.28	13.31	—	4.34	10.35
VOELCKER, 1877:									
(No data)	13.20	42.05	13.99	1.79	14.43	10.84	—	5.47	9.81
(No data)	8.63	38.17	12.68	0.79	14.07	17.50	—	8.94	8.22
(No data)	9.93	40.29	12.74	1.30	13.54	18.17	—	5.33	8.49
(No data)	14.28	40.12	14.76	1.70	15.46	11.17	—	4.22	8.88
(No data)	11.89	38.81	14.94	1.76	15.61	13.23	—	5.51	8.53
<i>Mean</i>	11.58	39.89	13.82	1.47	14.62	14.18	—	5.89	8.79
<i>Mean of all analyses^b</i>	8.66	46.37	13.93	3.88	11.89	14.72	[8.05]	5.04	8.98
PUNTA DE LOBOS									
RAIMONDI:									
Second zone	12.30	30.40	16.80	9.60	8.50	11.80	14.20	6.00	4.12
Third zone	7.20	19.30	25.97	6.50	23.03	20.30	1.30	2.90	2.60
Third zone	4.50	60.40	14.67	12.15	2.98	6.10	8.85	2.50	12.90
Third zone	3.20	24.80	15.03	4.50	12.47	30.00	8.00	6.50	0.67
Inferior polygon	10.20	34.60	15.29	13.00	2.71	29.70	6.30	1.20	4.56
<i>Mean</i>	7.48	33.90	17.55	9.15	9.94	19.38	7.73	3.82	4.97
VOELCKER, 1874:									
5 ft. on bed 20 ft. deep	14.53	35.77	15.34	3.20	14.36	17.15	—	2.85	6.55
40 ft.	14.06	49.74	11.01	1.21	11.59	12.24	—	1.35	9.99
8 ft.	4.76	17.14	10.95	0.38	12.51	26.66	—	27.94	2.64
<i>Mean</i>	11.12	34.30	12.43	1.60	12.82	18.68	—	10.71	6.39
VOELCKER, 1877:									
(No data)	7.67	29.53	19.09	1.44	20.89	17.89	—	4.92	5.88
(No data)	8.71	34.34	15.54	1.66	16.34	19.99	—	4.99	6.79
(No data)	7.97	32.32	16.71	1.37	18.18	20.91	—	3.94	6.05
(No data)	8.09	27.07	5.09	1.16	22.47	16.49	—	5.71	5.09
<i>Mean</i>	8.11	30.81	14.11	1.41	19.47	18.82	—	4.89	5.95
<i>Mean of all analyses^c</i>	8.90	33.00	14.69	4.05	14.08	18.96	[7.73]	6.47	5.77

* P₂O₅ sol. is included in the alkaline salts of Voelcker's, but not of Raimondi's, original analyses; the recorded quantity of P₂O₅ sol. has accordingly been deducted from the values of alkaline salts given by the former.

^b Heiden gives mean of 25 analyses for Ohlendorff: N 6.92%, P₂O₅ 14.18%, sand 6.61%, water 13.20%.

^c Heiden gives for mean of 25 analyses for Ohlendorff: N 5.70%, P₂O₅ 15.10%, sand 8.14%, water 14.12%.

TABLE 8—(continued)

	H ₂ O	Organic +NH ₃ salts	P ₂ O ₅ Total	P ₂ O ₅ Sol.	CaO, Re- corded as Ca ₃ P ₂ O ₈	Alka- line Salts	CaCO ₃ and Inert Matter	Sand	N
HUANILLOS									
RAIMONDI:									
Main slope	13.00	45.70	13.83	10.50	4.17	16.30	4.40	2.40	8.78
Second zone	10.70	30.70	14.95	10.00	5.85	11.40	22.20	2.40	8.42
Second zone	10.30	38.50	12.06	7.48	5.42	18.00	12.22	3.50	3.79
Second polygon of first zone	17.50	16.70	24.25	2.25	26.00	5.00	5.35	5.20	2.57
<i>Mean</i>	12.87	32.90	16.27	7.55	9.96	12.68	11.04	3.37	5.89
VOELCKER, 1874:									
5 ft.	8.23	46.46	15.62	5.33	12.16	13.89	—	3.64	10.40
10 ft.	5.25	41.90	15.30	1.47	16.37	15.26	—	5.91	7.45
19 ft.	12.67	34.83	16.65	1.44	17.99	14.25	—	3.61	6.72
13 ft.	15.36	34.21	12.93	1.62	13.40	21.47	—	2.60	6.65
40 ft.	8.66	47.09	14.35	3.26	13.11	13.39	—	3.40	8.81
<i>Mean</i>	10.03	40.89	14.97	2.62	14.60	15.65	—	3.83	7.91
VOELCKER, 1877:									
(No data)	22.41	31.14	13.97	2.91	13.08	14.68	—	4.71	7.65
(No data)	15.69	39.70	14.61	2.59	14.26	11.46	—	4.25	8.05
(No data)	17.60	36.85	13.85	2.88	12.98	14.71	—	4.01	7.86
(No data)	16.35	37.15	14.29	2.91	13.47	14.51	—	4.23	7.51
<i>Mean</i>	18.01	36.21	14.18	2.82	13.45	13.84	—	4.30	7.77
<i>Mean of all analyses^a</i>	13.64	36.67	15.14	4.33	12.81	14.05	[11.04]	3.38	7.19

^a Heiden gives mean of 25 analyses for Ohlendorff: N 6.60%, P₂O₅ 13.30%, sand 3.88%, water 14.12%.

posit consisted of hundreds of thousands of tons of guano.

CHRONOLOGICAL REMARKS ON THE CHILEAN COASTAL DEPOSITS

It is improbable that all the deposits that have just been described are of the same age. Some of the material that existed at Pabellón de Pica and Huanillos was certainly modern, in marked contrast to the known antiquity of the Punta Pichalo guanera. Brüggén is doubtless correct in regarding the low hills on the coastal terrace as having once had insular bird colonies, but it appears from Thierry's maps that a very large amount of the guano removed in the last century lay between these ancient islands, so that deposition must have continued for a time after the retreat of the sea. At Punta Pichalo the old guano apparently stopped accumulating rather before the advent of the makers of the shell fish-

hook culture, who apparently arrived before the last period of uplift was completed. Since there is evidence at least of intermittent guano production at Pabellón de Pica and Huanillos, up to the last century, or at Punta Pichalo even to the present time, there is nothing surprising in the bird colonies' depositing guano in the newly emerged areas between their original island homes, as the latter were elevated to their present position. Yet in most cases the existence of a marked crust, an overburden of sand and crust, and a slightly inland position of the guaneras, wherever the terrace is well developed, clearly suggest that the region became unsuitable for very large bird colonies fairly soon after the last emergence. It is possible that any large breeding colonies that managed to survive the uplift existed primarily on relatively inaccessible headlands, and that accessible colonies, as at Patillos, Patache,

TABLE 9*

	H ₂ O	Organic +NH ₃ Salts	P ₂ O ₅ Total	P ₂ O ₅ Sol.	CaO, Re- corded as Ca ₂ P ₂ O ₈	Alka- line Salts	CaCO ₃ and Inert Matter	Sand	N
	%	%	%	%	%	%	%	%	%
CHUCUMATA	5.20	7.60	7.79	0.64	8.46	9.70	17.46	43.80	0.56
PUNTA GRUESA:									
I	2.80	16.10	6.42	tr.	7.59	17.30	7.50	48.30	1.10
II	6.50	18.60	17.88	tr.	21.12	8.40	9.00	18.50	0.74
PATACHE									
I. Main section									
exploited	3.00	24.20	25.16	2.94	26.28	9.10	7.46	4.80	2.50
II. Second valley	5.40	51.60	14.67	9.40	6.24	8.30	3.80	10.00	10.71
III. Excavation no. 4	3.10	25.60	11.46	tr.	13.54	9.30	6.50	30.50	1.80
IV. Excavation no. 8	5.90	26.10	16.36	tr.	19.34	14.50	10.60	7.20	0.87
V. Excavation no. 9	1.30	25.30	20.91	3.96	20.00	23.20	6.74	2.50	1.27
VI. Excavation no. 11	4.00	49.70	17.07	9.50	8.95	10.10	8.80	1.40	8.24
VII	8.00	46.80	15.51	3.50	14.01	11.00	2.70	2.00	10.54
VIII	4.90	34.40	12.27	tr.	14.52	12.30	11.60	10.00	0.99
Mean	4.48	35.46	16.68	5.86	15.36	12.22	7.27	8.55	4.62
"POINTES DES PE- TITES PROMON- TOIRES":									
I	1.20	7.30	9.40	tr.	11.11	12.50	7.30	51.20	0.87
II	3.30	17.80	25.83	3.80	26.06	11.40	4.00	11.60	2.69
PATILLOS:									
North no. 1	4.80	41.80	15.97	10.24	6.78	13.90	10.26	6.50	9.89
North no. 2	2.80	32.40	18.26	2.68	18.43	7.80	14.32	6.00	4.52
CHIPANA:									
I	9.70	47.00	14.79	10.90	4.61	18.80	0.90	4.20	7.51
II. Slight elevation	5.00	40.90	16.78	4.50	14.52	11.40	9.60	1.60	9.15
III. Depth of 4.5 meters	9.40	38.50	16.19	1.30	17.61	14.70	0.10	2.50	5.89

* All analyses from Raimondi.

and Chipana, would be the first to suffer disturbance when their territories ceased to be insular. In general it would seem that, though Brügger may have overemphasized the association of the guano with old islands, it was clearly associated with a progressively descending shore line and presumably was mostly formed little prior to the advent of the makers of the shell fish-hook culture. It is, however, important to remember that there are indications of more complex changes of level at certain guaneras, where slight marine transgression over guano seems to have occurred. Whether these guaneras are older than the others or have merely suffered

special local disturbances of level, only renewed investigation can decide. In general, as Rivero first indicated, the buried guaneras of what is now the north Chilean coast indicate an extensive production of guano at a relatively remote time, apparently just antecedent to the first entry of man into the region.

At the time of the formation of the guano the Chilean coast must have supported a bird population comparable to that of Peru today. Since fossil or ancient guano appears not to occur north of Pisco Bay it is reasonable to suppose that at a time when the Peruvian coast was unsuitable for guano

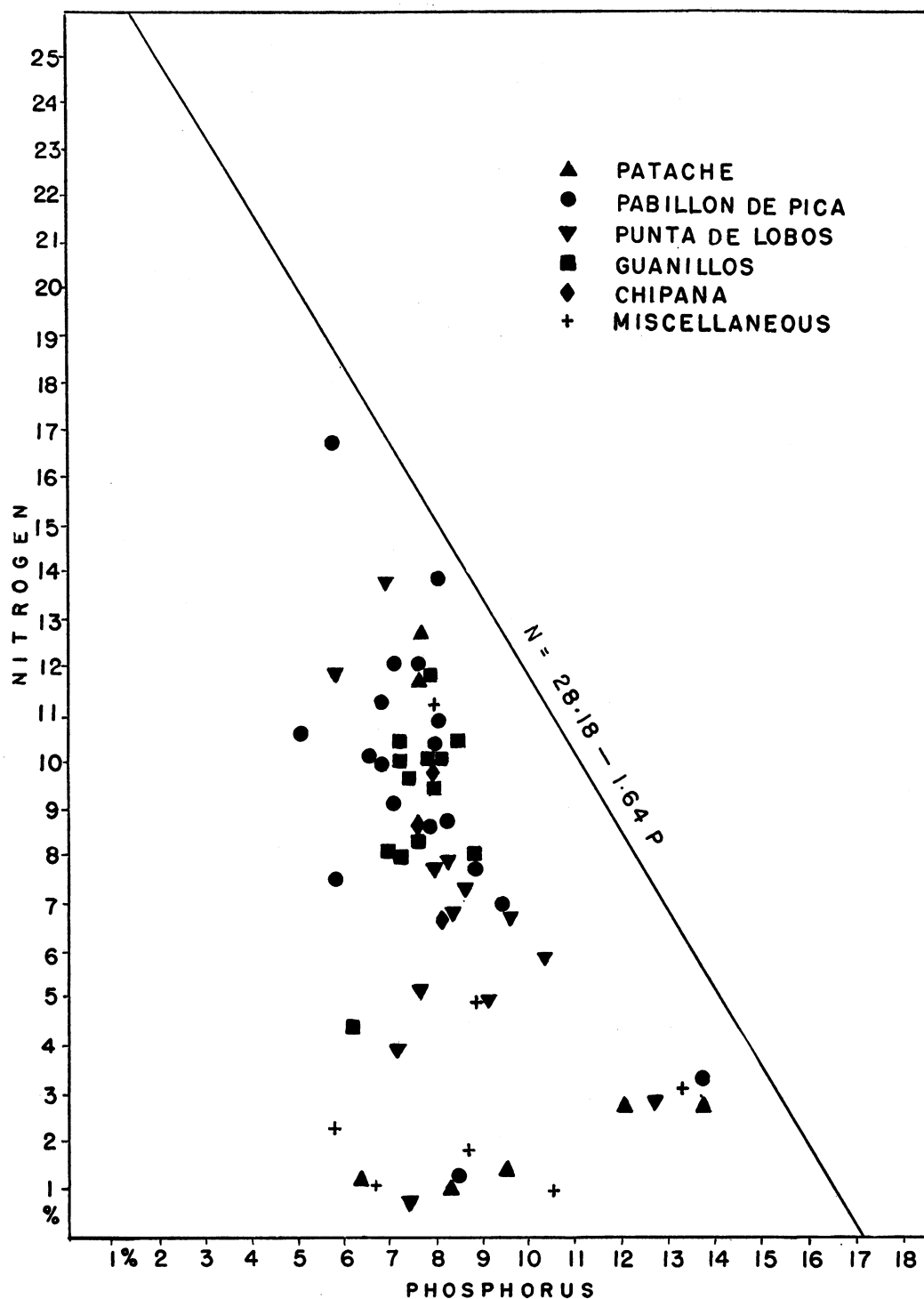


FIG. 29. Nitrogen contents of ancient Chilean guanacos plotted against phosphorus contents on a sand-free, water-free basis. The line of best fit from figure 20 has been added.

deposition, vast quantities of bird droppings could be accumulated in Chile. As the Peruvian islands became suitable, apparently the sea level was also falling, converting the Chilean islands into hills on the coastal terrace and making them unsuitable for the birds whose progeny must have largely moved northward up the coast.

INLAND GUANO DEPOSITS OF THE ATACAMA DESERT

Deposits of guano have from time to time been described from the inland desert of northern Chile. The first records are from between Antofagasta and Caracoles, notably between Cuevitas and Salinas, i.e., about latitude 23° 20' S. and at least 60 kilometers from the sea (Domeyko, 1874). Later deposits were discovered near Aguas Blancas, in latitude 24° 12' S. about 80 kilometers from the coast (Domeyko, 1878a; Villanueva, 1878) and from a region somewhat farther south, to the north and west of Agua Verde, at least 50 kilometers from the sea, between latitude 24° 55' and 25° 22' S. Ochsenius (1887) and Krull (1894) recorded similar occurrences. Much more recently Wetzel (1925, 1930) has described guano from the region of the Pampa del Toco Desert, in about latitude 22° S., inland from Tocopilla. These localities have produced bones and mummified bodies of birds. Some of the bones have been identified as possibly *Oceanodroma markhami* Salvin by Newton (1890), while better mummified specimens were determined as *Oceanodroma hornbyi* (Gray) and *Puffinus griseus* by Stresemann (1924, 1929; Wetzel, 1925, 1930). The modern breeding places of the first of these birds is unknown. Hornby's petrel and the sooty shearwater, however, still seem to breed inland in the region under discussion, though very little is known about their life histories (Phillipi, 1895; Stresemann, 1924, 1929; Murphy, 1936). Wetzel thinks that other species were probably present when the guano was formed.

The localities around Agua Verde are described by Villanueva (1878) as consisting of scattered patches, 5 or even 10 meters apart, spread over wide areas, of which the largest was about 700 by 230 meters. These areas presumably represent the sites of old bird colonies. Each patch had a central nucleus of

relatively pure guano, in a crack in the caliche surface of the desert; the peripheral parts of the guano patches are much contaminated. Even the central nucleus is seldom over 20 cm. thick.

Wetzel (1930) distinguished between nesting site guano (Brutplatzguano) and fissure guano (Spaltenguano). Nesting site guano occupies the sites of old bird colonies, and may often be covered by and mixed with sediment carried by catastrophic floods in the normally dry water courses. Fissure guano fills cracks in the desert surface.

In a specimen of nesting site guano, 34 species of diatoms were present. Of these 14 were determined by Hustedt as marine, from the Pacific Ocean, while the others were derived from a lake that once filled the Loa basin in the Pampa del Toco. The birds responsible for this deposit must therefore have fed in both the Pacific and the lake. Two specimens of guano are described by Wetzel as being rich in arthropodan remains, chiefly mites,¹ beetles, and pseudoscorpions, presumably largely carrion and dung feeding forms. The fissure guano described contained the extremity bones, with skin and hair, of *Lama vicuña*, with rodent (*Ctenomys*) skulls and bird remains. Forbes (1870, p. 253) indicates that the vicuña has the peculiar habit of depositing its dung in special localities, while Wetzel points out that rodents may be associated with such droppings. Murphy (1936) quotes a letter by H. D. Ball, who states that he had frequently found pockets of guano under 2 or 3 feet of hard cemented caliche in the same general region. This guano consisted of a dark brown, loosely cemented, sandy material, smelling strongly of iodine, and usually containing eggshell, bird bones, and insect remains. While it appears certain from this account and from vaguer statements by Villanueva, that the older desert guano formed prior to the final concentration of the nitrate deposits of the desert, Ball says gulls or guano birds still nest in the Río Loa Valley, and Wetzel was told of a nocturnal sea bird called the "garruma" that breeds on the nitrate plains. This bird, as

¹ Dr. Irwin M. Newell points out that figure 1 of Wetzel (1930) is probably a bird mite of the genus *Dermanyssus* Duges, though the specimen was rather large (ca. 1.3 mm.).

Murphy indicates, must be a petrel, perhaps *Oceanodroma hornbyi*.

These deposits, which are characterized by mummified vertebrate material and the chitinous remains of arthropods, differ considerably in their chemical composition from the nitrogenous guano of the South American coast.

Three partial analyses are available:

	CUEVITAS-SALINAS (DOMEYKO, 1874)	AGUAS BLANCAS (DOMEYKO, 1878A)	GRUETAS, PAMPA DEL TOCO (WETZEL, 1930)
N total	4.5-5%	12.0%	13.02%
P ₂ O ₅	1.3-2	4.3	3.89
Organic	n.d.	n.d.	68.36
Sand	37-40	n.d.	16.05

The bulk of Domeyko's first sample probably consisted of a mixture of sand and a relatively nitrogen-poor organic substance; his second sample is obviously comparable to that studied by Wetzel. The latter investigator's analyzed material consisted of a brown mass containing some NaCl and CaSO₄ crystals and a few flat pebbles. The total content of inorganic salts is given as 15.59%, in which 1.77% Cl, 1.97% SO₄, and 1.85% NH₃ nitrogen were present, but the full analysis is not presented. The organic material, in which the sample analyzed is specially rich, is composed of the mummified remains of organisms and consisted of C 41.2%, H 5.2%, O (by difference) 37.4%, and N 16.2%. This material is largely soluble in ammonia (54% in the main sample from Gruetas, 31% in another unspecified guano), giving a red solution of a humus-like material. The chitin-like organic matter in the residue contained C 38.4%, H 5.7%, O 37.9%, N 20.1%. This represents a great enrichment of nitrogen over the amount present in fresh chitin, which contains 6.4% N. Solutions of the original guano gave neither the biuret nor the ninhydrin reactions. Wetzel thinks that under the peculiar conditions of dry oxidative weathering, carbon is lost from the protein and chitin of the original animal material, while the nitrogen is retained. The ordinary nitrogen compounds of coastal avian guano appear to be absent, so that in spite of the high organic and low phosphorus contents the desert and coastal guanos are obviously very different, the former evidently containing far less excretory and more necrotic material than the latter.

ELEVATED ANCIENT GUANO ON THE MEJILLONES PENINSULA

While the buried guano of the larger guaneras of the Chilean coast has in general undergone but limited diagenetic change and has retained a large part of its original nitrogen, one group of extensive deposits of a leached phosphatic guano is known from the

southern part of the region. This group of guaneras is found at a considerable altitude on the Mejillones Peninsula. Brüggén (1938, 1939a, 1939b) who has recently studied the deposits, believes that they lie on elevated fragments of the main coastal terrace that have been uplifted by local earth movements since the deposition of the guano. From his account there is no good reason to believe that the Mejillones guaneras are older than the other deposits of ancient guano on the Chilean coast. The peculiar chemical character of the guano of the Mejillones deposits is to be ascribed partly to the action of sea water and partly to the mists that frequently envelop the mountain peaks of the peninsula.

The Mejillones Peninsula is a block of much faulted granite and syenite, connected with the coast by a low plain, 100 to 200 meters above sea level, bearing marine shells (Domeyko, 1878b, 1880). The peninsula bears a number of peaks, Morro Moreno at the south, Bandurrias in its center, Morro de Mejillones and the two Las Tetras at the north. Except perhaps for the first named, these rise out of elevated plateaus defined by fault scarps and regarded by Brüggén as uplifted fragments of the coastal terrace. A number of shore lines are visible, particularly above the Bay of Mejillones. These were mapped by Krull (1894) who believed that nine marine stages were represented. Brüggén, however, concludes that Krull's terraces 5 and 6 north of the Morro de Mejillones are equivalent to his terraces 7 to 9 around the Morro, and that the scarp separating the latter from the northern part of the peninsula

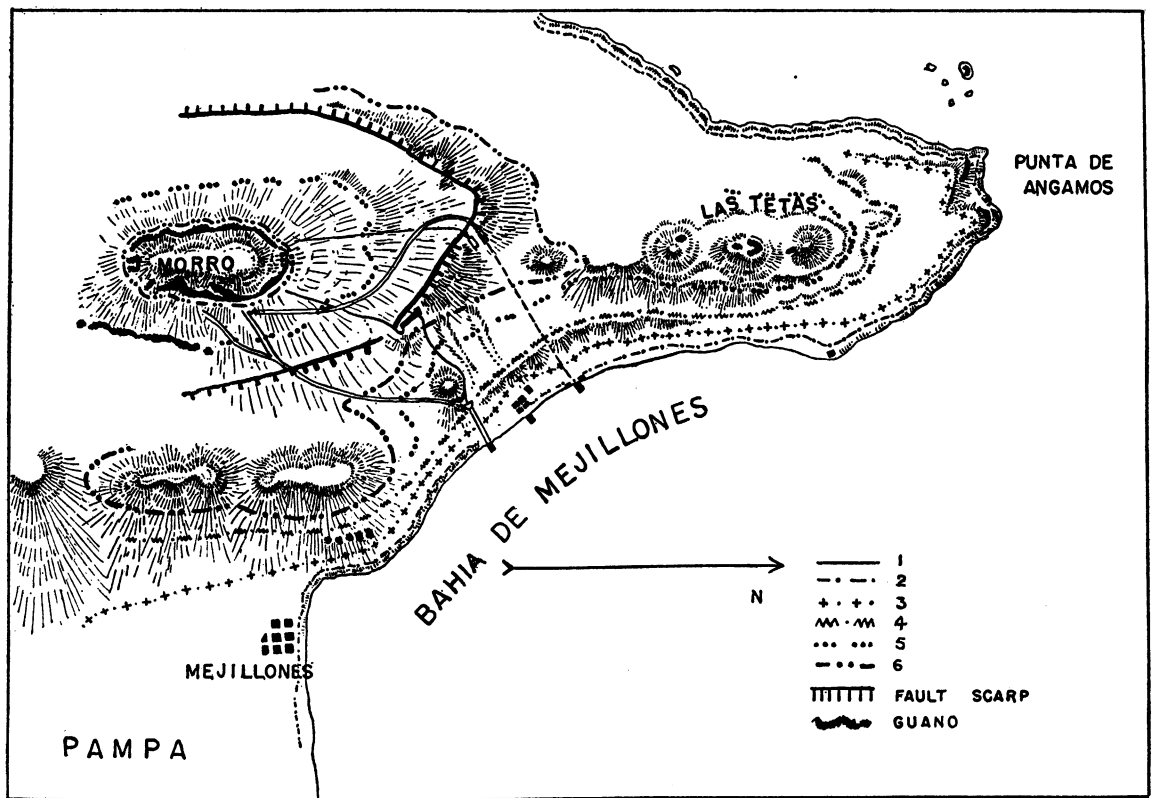


FIG. 30. The Mejillones Peninsula, showing fault scarps and raised beaches.
Modified from Krull and from Brügger.

is due to a fault. The general morphology of the northern part of the peninsula is therefore interpreted by Brügger as consisting of a fragment of the terrace raised to about 500 meters or perhaps a little more, from which the Morro projects to 671 meters, and another fragment raised to 200 to 280 meters from which Las Tetás project. A small terrace overlooking the sea at Point Angamos at the extreme north may represent another piece of the same system (fig. 30).

Below these elevated terraces, the lower four of Krull's strand lines, placed by him at 1.50 meters, 16.50 meters, 39 meters, and 126 meters, may presumably be accepted as representing stages in the uplift of the peninsula as a whole. Larroque (1863), who gave the earliest extensive account of the locality, stated that marine shells occur up to about 200 meters but no higher. Krull, however, noted that the majority of the shells were associated with his fifth and eighth beaches at 223 meters and 490 meters, respectively.

Both of these occurrences are, if Brügger's interpretation be accepted, likely to be contemporaneous or nearly so. Krull says that many shells retain their coloration and that they belong to modern species.

At the northern end of the peninsula, the rocky Point Angamos yielded small amounts of an absolutely fresh, highly nitrogenous white guano, which was collected with great difficulty by hand and fetched a high price. It is evident from Brügger's account that birds resting at night still deposit guano on these inaccessible rocks. This Angamos material must not be confused with the old guano colorado of the elevated deposits. Ancient guano is found deposited (Larroque, 1863; Domeyko, 1878b, 1880; Krull, 1894; Brügger, 1938, 1939a, 1939b) around the base of the Morro, at an altitude of about 590 meters on Krull's map, which appears to be excessive from Brügger's account. There are also deposits around Las Tetás, particularly the northern of the two, and some is possibly

associated with the small peak, formerly an island but now elevated to form Cerro Bandurrias. Larroque's section indicates guano on the eastern side of the peninsula at a somewhat lower level than that of the main deposit, and this guano is indicated on Krull's map. Brüggen also notes a small deposit in a gully opening onto the terrace at 100 meters above the sea, at Point Angamos.

The principal guanera at Mejillones forms a broad band running around the base of the Morro. The band is stated to be about 50

sidered that typically the deposit lay on a white argillaceous substance, locally called tosca, below which is fragmented and decomposed rock from the Morro. A fourth section given by Larroque (fig. 34) shows guano (B, D) lying on a white porous material (C, E), presumably the tosca of the other writers. Below this Larroque indicates an earthy stratum (F) containing granite fragments different from those derived from the Morro, and presumably forming a beach deposit. Altered granite of the Morro lay below this.

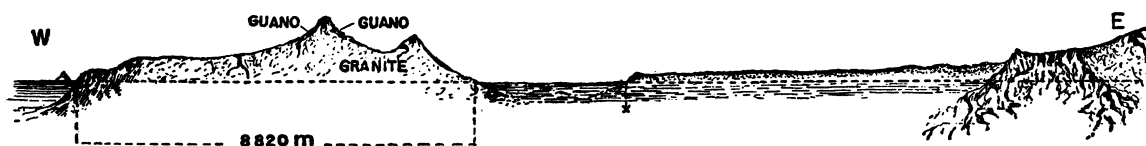


FIG. 31. Transverse section through the Mejillones Peninsula. After Larroque.

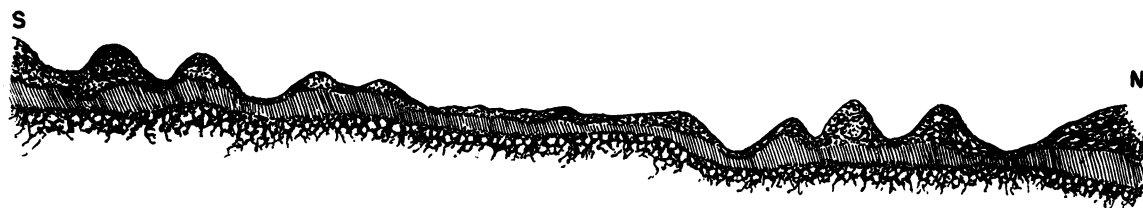


FIG. 32. Longitudinal section through the main guano deposit, Mejillones. After Larroque.

meters wide by Larroque and by Domeyko (1878b) but is 100 to 150 meters wide according to Krull (1894). The guano varied in thickness from about 2 meters to about 13 meters and was usually covered with 10 to 20 meters of overburden, characterized as an "agglomerado salino-arenaceo" by Larroque (figs. 31-34). On the eastern side of the Morro the deposits tended to occupy rounded indentations in the base of the peak. These are excavated less deeply than the typical caletones of the Chilean coastal guaneras. In some places the guano is said to have been piled up against almost vertical walls of rock and to be covered with rock debris. On the western side of the Morro the deposits seem to have been more diffuse and less pure. The profile of the bedrock indicates that before the guano began to accumulate a barrier in the form of a row of small islets must have lain outside the region of deposition.

Though three of Larroque's sections indicate the guano lying on a layer of fragmented and decomposed granite, Domeyko con-

sidered that typically the deposit lay on a white argillaceous substance, locally called tosca, below which is fragmented and decomposed rock from the Morro.

An analysis by Krull (I) indicates ferric phosphate and calcium phosphates to be present, but very similar analyses by Domeyko (II, III) are said to refer not to the tosca but to guano between and above layers of tosca.

	I	II	III
H ₂ O, ign.			
loss	13.8%	14.40%	11.10%
FePO ₄	13.5	13.25	13.55
CaO	18.3	16.05	20.60
MgO	1.4	1.44	1.32
P ₂ O ₅	20	19.12	21.00
SO ₃	2.1	2.23	1.96
Insol.	30.4	30.80	30.00
	(Kaolinitic)	(Sandy)	(Sandy)

Brüggen regards the tosca as largely precipitated calcium phosphates. It is probable that the composition varied from place to place. The ferric phosphate of Domeyko's and Krull's analysis is interesting, indicating the action of phosphatic solutions on the decomposition products of the bedrock. Lar-

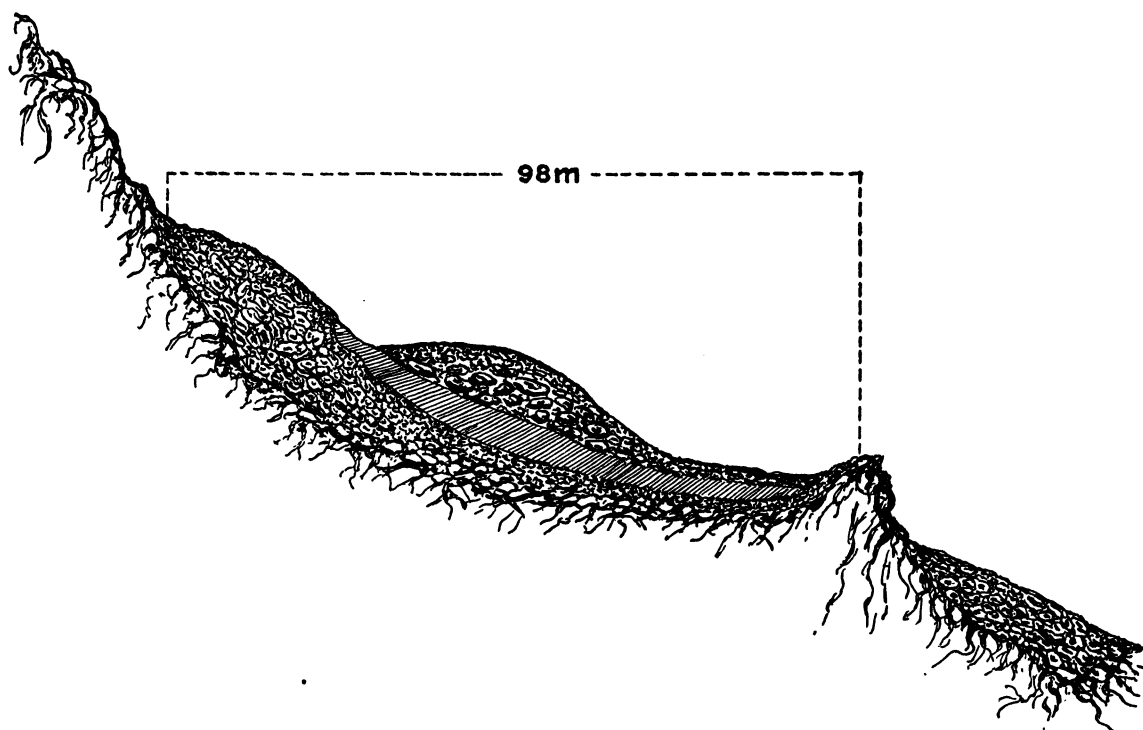


FIG. 33. Transverse section of guano deposit, Mejillones. After Larroque.

roque, moreover, indicates that the surface of granite fragments embedded in the pure guano and the fractured granite under the deposit shows evidence of alteration, the greenish gray surface of the unaltered rock becoming pink. In some places layers of an impure earthy guano locally called *ripio* were intercalated between purer material. The upper layer (C) of white porous material in the section reproduced from Larroque in figure 34 may represent this substance. Profiles studied by Domeyko from the northeastern part of the deposit indicate a superficial layer of rock fragments, lying over up to 19 feet of *ripio* or impure guano containing borophosphatic concretions. Below this were one or two layers of purer guano with some borophosphate nodules, with *tosca* or phosphate-free, kaolin-like material and some *ripio* below the purer guano layers. The figure supposed to show such a profile does not seem to have been printed in Domeyko's paper. An official survey by Esmeralda (Voelcker, 1876) conducted in 1870 gave the initial reserve as between 2,000,000 and 4,000,000 tons. Krull says that

after 200,000 tons had been exported, reports were circulated in Europe that the deposit was exhausted. He points out, however, that the estimate of 4,000,000 tons assumes a layer of guano of 10 meters mean thickness and 100 meters mean width which appears from his account to be not unreasonable. No less than 216,457 tons of Mejillones guano were received at the port of Hamburg between 1871 and 1883 (Heiden, 1887). Exploitation is apparently still taking place.

In one small ravine in the south-southeast projection of the Morro, a deposit of bird bones in a yellow guano was discovered, but otherwise the deposit apparently contains no fossils. Krull speaks of these bones as belonging to the "*pájaro-niño* o *Piquero* Penguin." Philippi (1895) described the fossils as *Sula antiqua*, a supposed precursor of *S. variegata* but exhibiting certain differences from the latter. Murphy (1936), however, considers the differences as practically nonexistent.

The purer Mejillones guano appears to have been reddish. Krull speaks of an at-

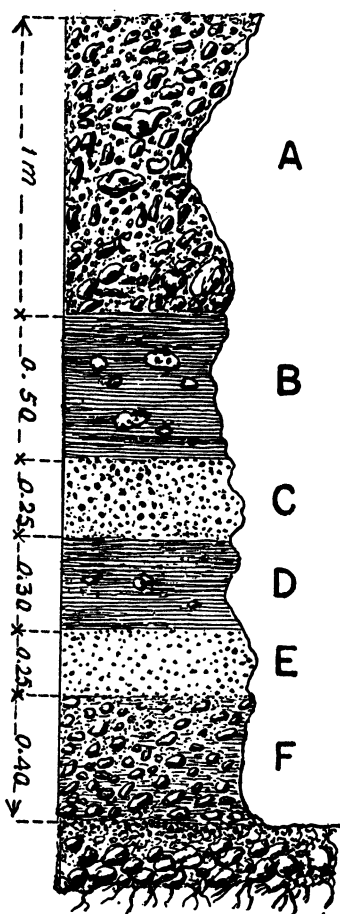


FIG. 34. Section through part of the Mejillones deposit. After Larroque.

tractive brownish orange color, but says that on exposure to the air the color faded. Such material was earthy but often contained crystalline inclusions. There was also material apparently due to the crystallization of salts in solution, and in some cases the guano is described as crystalline. Some parts of the deposit seem to have been rich in nodules of gypsum and other substances, including the

remarkable magnesium borophosphate discussed below. The analyses in table 10 were probably made on the more typical earthy guano.

It is clear that even in Voelcker's samples the phosphate cannot all be regarded as present as a hydroxylapatite-like material as seems to be the case in many leached guanos. The molecular ratio of total $\text{CaO}:\text{P}_2\text{O}_5$ is, for the mean of Voelcker's more completely analyzed specimens, 0.346, but if the sulphate and carbonate are both present as calcium salts, which seems almost certain, the corrected ratio would be 1:0.397. Some of the phosphate was, however, undoubtedly present as magnesium rather than calcium salts; such magnesium phosphates were evidently very characteristic of the locality.

Voelcker indicated, as did Krull, that the reddish color of the earthy guano from Mejillones is due to an organic material, which Krull speaks of as humic, and which decomposes on exposure to air.

In addition to the earthy guano, Domeyko mentions an indurated guano and also a crystalline guano, as well as specific mineral inclusions. The indurated guano is said to have been blackish gray, more or less homogeneous and composed mainly of calcium triphosphate, with some hydrated biphosphate, presumably as brushite, mixed with calcium sulphate, presumably as gypsum, a substance that seems to have been rather common in the less pure parts of the deposit. Two (I, II) samples of crystalline guano from the north side of the deposit were analyzed by Krull (*in* Domeyko, 1878b), and a third analysis (III) of material said to come from cracks in the rock was added in a later paper (Domeyko, 1880), while a fourth (IV) analysis was given by both Domeyko (1878b) and Krull (1894) for a hard crystalline guano adherent to the rock of the southern side of the Morro:

	I	II	III	IV
H_2O with trace of org.	31.00%	17.60%	36.00%	31.88%
CaO	7.10	17.70	5.80	6.55
MgO	24.50	19.10	18.53	16.52
P_2O_5	36.00	39.00	40.13	34.47
Fe_2O_3	—	—	—	1.11
SO_3	tr.	tr.	—	4.47
NaCl	tr.	tr.	—	0.89
Insol.	—	—	—	0.80

TABLE 10

	Vohl <i>in</i> Krull (1894)	Liebig <i>in</i> Krull (1894)	Fresenius <i>in</i> Krull (1894)	Voelcker (1876)	
				Extremes	Mean
Water	7.7%	2.1%	3.1%	(6.38)* 6.61–8.76%	7.47
Organic matter, NH ₃ , comb. H ₂ O	6.5	9.3	6.5	6.28–7.44	6.98
P ₂ O ₅	35.9	39.1	38.4	30.72–34.40 (35.25)	32.47
CaO	30.7	39.7	34.4	(35.50) 36.42–37.60	36.93
MgO	7.9	1.4	6.5	2.83, 3.42 (2 anal.)	3.13
Fe ₂ O ₃	0.2	0.4	0.04	0.38–0.69 (5 anal.)	0.53
Na ₂ O	1.5	2.3	1.4	0.97–1.52 (4 anal.)	1.28
K ₂ O	0.5	0.2	—	0.34 (1 anal.)	0.34
Cl	2.3	2.0	2.3	1.11–1.74 (4 anal.)	1.46
SO ₃	1.6	1.7	1.7	1.68–6.76	4.52
CO ₂	1.6	—	—	0.45–2.76	1.22
SiO ₂ and insol.	2.5	1.7	2.8	1.23–2.47 (4.39)	1.73
N total	0.7	0.7	0.7	(0.72) 0.79–0.98	0.90

* Values in parentheses refer to an incomplete analysis which happens to give the highest P₂O₅ of any of the samples studied by Voelcker.

Analysis I and II are also given by Krull as supposed examples of magnesium hydrogen phosphate in which some of the magnesium is replaced by calcium.

Mineralogically the Mejillones deposit was characterized, as is indeed apparent in the analyses just given, by the presence of magnesium phosphates, so differing from the nitrogenous guano of Guañape with its very soluble crystalline sulphate and oxalate minerals, and from the fully leached phosphatic guanos of most of the drier tropical bird islands on which the main biogeochemical mineral is an apatite-like material, associated in some cases with less basic calcium phosphates. Though Brüggen is doubtless correct in assigning the source of the magnesium to sea water, it is very improbable that the minerals found at Mejillones would have survived in the deposit unless the climate had been somewhat drier than that of the majority of the localities where only calcium phosphates are known. Brüggen indicates that the concretions of phosphatic material con-

taining magnesium are commonest in the southern part of the guanera and that similar concretions are known on the southern parts of the guaneras of Pabellón de Pica and Huanillos. This localization is evidently dependent on the prevalent southern direction of the wind, which could drive sea spray onto the guano before the elevation of the coast line and the uplift of the Mejillones Peninsula.

Newberyite, MgHPO₄·3H₂O, was recorded by Schmidt (1883) as forming small crystals in brown guano. The material was determined without analysis, by its crystallographic and optical properties. Elongate fibrous crystals occurring in earthy guano and apparently referable to this mineral were analyzed by Domeyko (I), while Krull gives an analysis (II) clearly referring to the same substance and three analyses purporting to refer to a crystalline mineral of like composition but in which one-sixth of the magnesium is replaced by calcium. Two of these analyses have already been given, the third analysis (III) agrees with his hypothesis, but the agreement is presumably fortuitous.

	I	II	III	MgHPO ₄ ·3H ₂ O
MgO	22.70%	23.06%	18.53%	23.1%
CaO	—	—	5.80	—
P ₂ O ₅	41.94	40.54	40.13	40.7
H ₂ O	35.36	36	36	36.2

Bobierrite, $\text{Mg}_3\text{P}_2\text{O}_8 \cdot 8\text{H}_2\text{O}$, was first described from Mejillones (Bobierre, 1868; Lacroix, 1888), though it is now known from other localities, where it may be formed by the action of ground water upon bones. Bobierre regarded the material (II, III) as a heptahydrate, and Krull interprets his analysis (IV) of Mejillones material in the same way. Lacroix's analysis (I) is undoubtedly superior to those of the other workers and is based on type material from Bobierre's collection. It is probably recalculated to exclude impurities and agrees very well with the accepted octohydrate formula. Bobierre states that the mineral formed small white crystals in earthy guano.

	I	II	III	IV	$\text{Mg}_3\text{P}_2\text{O}_8 \cdot 8\text{H}_2\text{O}$
MgO	29.97%	26.00%	26.28%	29.80%	29.7%
P_2O_5	34.59	33.00	32.52	34.82	34.9
H_2O	35.38	34.00	33.88	33.65	35.4
$(\text{Al, Fe})_2\text{O}_3$	—	3.00	1.97	—	—
NaCl	—	0.53	0.55	—	—
Insol.	—	1.00	0.98	—	—

Magnesium borophosphate, of unknown mineralogical composition, is recorded by Domeyko (1878b, 1880) and by Krull (1894) as forming concretions, mainly in the ripio or impure earthy guano of Mejillones, but also, more rarely, in the purer parts of the deposit. These spherical or kidney-shaped concretions are not more than 5 to 6 cm. in diameter and are soft externally; they have therefore probably suffered alteration since they were formed. Internally the hard resistant material seemed to Domeyko to be amorphous, but Krull had pure crystalline material (I, II) corresponding to $3\text{MgO} \cdot \text{P}_2\text{O}_5 \cdot \text{B}_2\text{O}_3 \cdot 9\text{H}_2\text{O}$. He regarded the analyses III and IV as representing less pure material and from analyses V, VI, and VII by Domeyko, he concluded, probably erroneously, that Al_2O_3 replaces part of the B_2O_3 in some specimens.

	I	II	III	IV	V	VI	VII
MgO	24.6%	24.7%	23.2%	20.4 %	24.38%	24.45%	20.5%
CaO	—	—	1.9	6.6	0.14	0.14	—
Al_2O_3	—	—	—	—	2.30	18.70	29.2
P_2O_5	28.7	28.8	29.5	29.0	27.6	16.05	10.9
B_2O_3	14.5	14.5	11.6	10.0	6.80	6.78	4.2
H_2O	33.1	32.2	33.8	33.13	38.30	33.70	35

It is most unfortunate that there is no modern study of this interesting mineral. Krull was at a loss to explain the origin of the boron, but it can clearly have come from sea water.

In addition to these magnesium phosphate minerals, halite, gypsum, and, as has been indicated above, probably brushite were present in the Mejillones deposits. The presence of iron and aluminum phosphate minerals is also evident, but no information is available as to their nature. Lacroix (1888), moreover, records stercoreite and an orthorhombic oxalate of ammonia and soda from Mejillones. These last two records are very doubtful. An oxalate of the same qualitative composition, also associated with stercoreite, is recorded in an earlier paper (Lacroix,

1886) as replacing a bird's egg from Peruvian guano without precise locality. It seems almost certain that the two records refer to the same specimen of oxalate. In the later paper Lacroix expressly states that his material of bobierrite came from Bobierre's collection, and adds the record of stercoreite and the oxalate in a final paragraph, also quoting Schmidt's record of newberyite. The oxalate, of which no quantitative analysis was ever made, is presumably oxammite, which is known to replace eggs in nitrogenous guano; stercoreite is also known to occur in nitrogenous Peruvian guano. No indication of any guano minerals freely soluble in water has otherwise been given for the Mejillones deposit. It seems therefore probable that Lacroix did not fully realize that there were other sources of guano minerals

than Mejillones. This supposition is reasonable because if he had been aware of either Raimondi's or Shepard's contributions he would have known that the oxalate was not a new mineral. Not realizing that there were

many possible localities from which his stercorite and oxalate might have come, he probably recorded them from the only locality known to him to produce guano minerals.

MINOR DEPOSITS IN THE OCEANIC PART OF THE PERU CURRENT AND ELSEWHERE OFF THE WESTERN COAST OF SOUTH AMERICA

There have been three reports of guano or of metasomatic phosphatization on groups of islands far off the South American coasts. None of these deposits were of any great commercial importance, though that on Malpelo Island is of considerable scientific interest. The first two reports relate to localities within the eastern limb of the South Pacific Gyral, though far from the region of upwelling. Malpelo Island, lying farther to the north, is in the region of the Equatorial Counter Current in the northern summer and apparently in a region of convergence within the current flowing south from the Gulf of Panama in the southern summer.

SAN AMBROSIO

LATITUDE 26° 32' S., LONGITUDE 79° 58' W.

SAN FELIX

LATITUDE 26° 24' S., LONGITUDE 80° 16' W.

Two volcanic islands lying nearly 900 kilometers from the Chilean coast, and so far outside the region of the Peru Coastal Current. Both islands are rather over 2 kilometers long, but San Ambrosio rises to a height of 479 meters, while the highest point on San Felix reaches only to 193 meters. It is evident from the barren appearance of the islands that they are relatively dry. The "Atlas of climatic charts of the oceans" (McDonald, 1938) indicates that steady rain may be expected only on from 1% to 5% of the occasions of observation in this part of the Pacific. In the summer, from December to February, the incidence of all forms of precipitation lies within the same limits, but from March to November the expectation from drizzle is evidently higher, some forms of precipitation being reported on between 5% and 10% of the occasions of observation. The islands are definitely wetter than is the northern coast of Chile. It is probable that the summit of San Ambrosio receives additional orographic rain.

The bird colonies on both islands appear to have been very extensive, though Willis and Washington (1924) state that a very great mortality occurred on San Felix as the result of the emanation of volcanic gases at the time of the Chilean earthquake of 1922. According to Morrell (1852) large numbers of sea birds could be obtained on San Ambrosio in January and February. The species inhabiting the islands are not well known and have been investigated only in quite recent years. It is possible that prior to the earthquake the populations were not merely greater than in 1935 when Chapin (*in* Murphy, 1936) visited the islands, but also specifically more varied. *Sula dactylatra* is the only booby recorded. Willis (*in* Murphy) indicates that these boobies were extremely numerous in October, 1922, before the earthquake. *Sterna fuscata*, *Procelsterna albigutta*,¹ and *Anous stolidus* are the only terns reliably recorded from the island. *Pterodroma neglecta* is found on San Ambrosio, *P. cookii delippiana* on San Felix and its outlying islets. The only other sea bird certainly known from the group is *Fregetta g. grallaria* (Murphy, 1936).

According to a letter of Rear Admiral Moresby to the Secretary of the Admiralty (Great Britain, Parliamentary Sessional Papers, 1857) the east island of San Felix had a stratum of guano at its apex, and the plain of the west island was recently whitened by birds. It is possible that these records refer respectively to the inaccessible islet of Gonzales to the southeast of San Felix and to the main island itself. The northwest bluff of San Felix was examined by W. H. Crane who found lava whitened by bird's dung. G. H. Parkin is said by Moresby to have examined

¹ So recorded by Murphy (1936). According to Peters (1934) *Procelsterna* is monotypic, and the San Ambrosio bird is *P. cerulea imitatrix* Mathews.

San Ambrosio and found a light deposit on the sides of the island. A specimen appears to have been sent to London, but it has not been possible to find any published analysis. Parkin noted but few birds.

Willis speaks not merely of being told of the great number of boobies, but indicates that in October, 1922, San Felix was covered with guano. Chapin also mentions that guano had been present and attributes it to *Sula dactylatra*. Murphy says that the guano was nitrogenous enough for it to be imported into Chile; it is unfortunate that this somewhat obscure analytical criterion is the only one that the published evidence indicates has been applied to the guano of these islands.

THE GALÁPAGOS ISLANDS

MOSTLY BETWEEN LATITUDES $0^{\circ} 30'$ N. AND $1^{\circ} 30'$ S. AND LONGITUDES 89° W. AND 92° W.

These islands lie in a region of considerable hydrographic complexity. The cool waters of the Peru Current swing round to the west in these latitudes and run parallel with warmer water of the South Equatorial Current from the coasts of northern South America. Streaks and patches of warm and cold water occur frequently in the region. The water is apparently greenish rather than of an oceanic blue tint, and it is probable that there is considerable local upwelling. The climate is generally semi-arid, at least at sea level, with irregular seasonal rains in the early part of the year, from January to May. The general ecological conditions would appear to favor the accumulation of at least phosphatic or leached guano. There is moreover a well-developed marine avifauna; Murphy (1936), who gives a good general account of the islands, lists 19 species, of which several, notably *Sula dactylatra*, are guano birds of some importance elsewhere.

In spite of the inherent likelihood that an archipelago having the general climatological and biological characters of the Galápagos Islands would include some guano islets, there is very little evidence that any significant deposits were ever found on any members of the group.

Prior to 1854, reports of immense guano deposits were circulated and a good deal of political and legal maneuvering was undertaken by the Ecuadorean General José Vil-

lamil, who had been governor of the islands, and by Judah P. Benjamin of New Orleans on behalf of Julius de Brissot of that city. The negotiations aroused the suspicions of England, France, and Spain, but after a good deal of excitement it became apparent that the supposed guano deposits did not exist. The guano treaty between the United States and Ecuador, which had evoked the suspicion of the European powers, accordingly never materialized. The matter has been briefly discussed by Beebe (1924) and more recently and at greater length by Gruss (1940), who had access to the relevant papers in the Latin-American archives of the United States Department of State.

Boussingault (1860a) gives the following analysis of Galápagos guano, received from the Ecuadorean government without details of its occurrence:

$\text{Ca}_3\text{P}_2\text{O}_8$	60.3%
N total	0.7
N. NO_3	0.4*
Sand and clay	19.0

* Nitrate equivalent to 3% KNO_3 .

The only other information relating to biogeochemical phosphate deposition on the islands is a statement by Mann (1909), referred to by Murphy (1936), that guano glass, comparable to that observed on St. Paul's Rocks and on Lobos Islands off the coast of Peru, exists on Barrington Island, one of the smaller members of the Galápagos group.

MALPELO ISLAND

LATITUDE $3^{\circ} 59'$ N., LONGITUDE $81^{\circ} 34'$ W.

A virtually inaccessible volcanic island, 258 meters high and about 2 kilometers long. It lies in a region through which the Equatorial Counter Current flows throughout a large part of the year, but during the late summer the island is situated in a current flowing south from the coasts of Central America. Local conditions are probably complex; very violent currents are said to cause the appearance of breakers around the island in spite of its being steep (United States Hydrographic Office, 1916a). The rainfall of the region in which Malpelo Island lies is great, but apparently seasonal; according to the "Atlas of climatic charts of the oceans" (McDonald,

1938) steady rain may be expected on 5% to 10% of occasions from June to August and on 15% to 20% of occasions from September to November.

Malpelo Island evidently supports a fair bird population, the most abundant species being *Sula dactylatra*, of which perhaps 15,000 pairs breed on the island. The climatic and physiographic conditions are obviously not favorable to the accumulation of guano, which must be washed down the sides of the island almost as soon as it is formed. The volcanic rock is, however, extensively fractured and has been greatly phosphatized, probably mainly in the vicinity of the fractures, by percolating guano solutions. McConnell (1943) has made an interesting study of the

results of the phosphatization. Phosphatic solutions, percolating through fractures, have changed an amygdaloid, originally a hydrothermally metamorphosed scoria, into a rock now consisting of secondary quartz replacing feldspar, chlorite, and phosphate minerals. The phosphate is identified as a mixture of the pair of isodimorphous aluminum phosphates $\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$, variscite and meta-variscite. Another specimen from Malpelo exhibits rather complete replacement of a diabasic rock, similar to the augite-andesite known to form parts of the island, by the isodimorphous pair of ferric phosphates $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$, strengite and phosphosiderite. In neither specimen is there any evidence of the previous formation of calcium phosphate.

GUANO DEPOSITS ON THE COAST OF LOWER CALIFORNIA

OCEANOGRAPHY

A good summary of the oceanography of the region is given by Sverdrup, Johnson, and Fleming (1942), and by Sverdrup (1944); the latter work gives a full historic background. The California Current flows southward between latitudes 48° N. and 23° N. along the coast of western North America. The current represents a slow movement of subarctic water towards lower latitudes and may be regarded as the deflected continuation of the Aleutian Current of the northern part of the Pacific Ocean. During the spring and early summer, when north-northwest winds on the eastern side of the high pressure region in latitudes 30° to 40° N. and longitudes 135° to 150° W. prevail, the California Current is the Northern Hemisphere counterpart of the Peru Current. The wind and current both proceed along the coast, but as the current tends to flow to the right of the wind, coastal upwelling inevitably occurs, as Thorade (1909) first indicated. Areas of such upwelling are found along the coast. From these areas tongues of cold water move southward away from the coast and are separated from each other by tongues moving northwards towards the coast. The swirls thus formed are obviously analogous to those off the coast of Peru. Two conspicuous centers of upwelling are known in latitudes 35° N. and 41° N. Of more interest in the present work

are Thorade's report of a center of upwelling at about latitude 24° N. and Osorio Tafall's (1944) more recent finding of upwelling off Point Abreojos (about latitude $26^\circ 40'$ N.) and in the vicinity of Adelaida Island. Osorio Tafall notes that around Cedros Island and the San Benito Islands warmer water than that to the north and south was encountered. It is probable that warm and cold tongues analogous to those off the Peruvian coast account for his observations. The upwelling water is derived from comparatively small depths, probably of less than 200 meters, but its presence is reflected in the large diatom production along the coast, and the consequent high productivity of different levels of consumer organisms.

During the late summer the meteorological conditions off California change. The regular swirls break up into numerous irregular eddies, and by January a counter current flowing north to latitude 48° N. has developed. It appears that when a current flows along a coast such counter currents tend to develop in the absence of a prevailing wind.

The general picture presented by the California coast is obviously but a poor and temporary analogy to the more grandiose and constant phenomena off Peru. If the temperature distributions on the two coasts be considered in broad outline, the 20° C. isotherm normally intersects the coast of Peru north

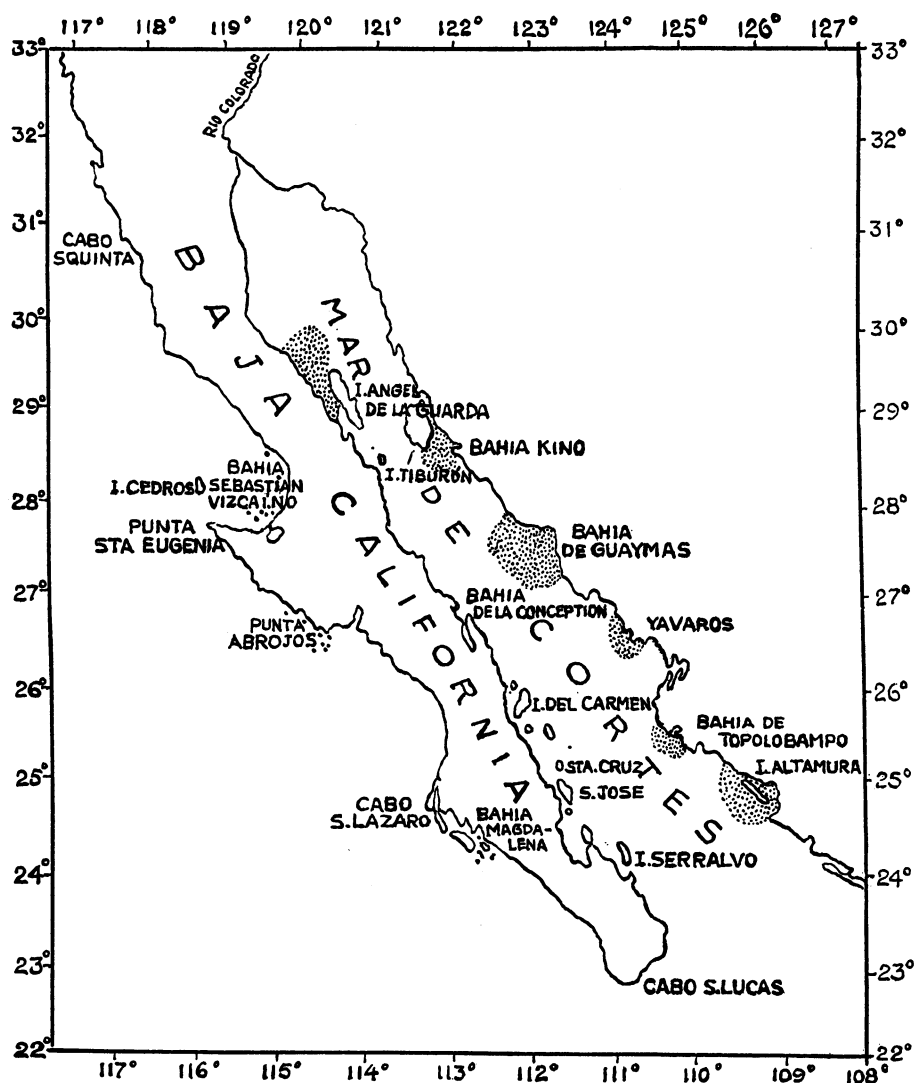


FIG. 35. Zones of high plankton production and position of the more important guano islands off the coast of Lower California.

of latitude 10° S. at all seasons, while the intersection with the coast of California oscillates annually between 23° and 28° N. It is, however, important to note that the current system comparable to that off Peru is developed off California during the season when normally the greatest trophogenesis occurs in any locality. Some of the biological advantages of such a system will be carried up the levels of food chains from diatoms to fishes over a much longer period than that during which determining physical conditions exist (cf. Sverdrup, 1944).

Osorio Tafall (1944) finds that although

the general phytoplankton of the Pacific coast of Lower California is richer than in the open Pacific, it does not show the extreme development found within the Gulf of California. Three regions appear to be especially rich and in consequence constitute zones of notably good fish production. These zones are Magdalena Bay, about latitude $24^{\circ} 30'$ N., the region off Punta Abrejos, about latitude $26^{\circ} 40'$ N., and Sebastian Vizcaño Bay, about latitude 28° N. These regions are marked in figure 35 but are less reliably indicated than the productive zones within the gulf for which Osorio Tafall (1943) gives a

map rather than merely verbal indications of positions.

The enhanced productivity of the California coast permits the development of rich fisheries, notably of the sardine *Sardinops caerulea*, a species breeding from Magdalena Bay northward to Point Conception, though chiefly in the northern part of this coast, outside the region of guano deposition, and migrating northward in summer to the coast of Vancouver Island (Clark, 1940). Other small fish, with less well understood life histories, are also abundant. Osorio Tafall states that the food of the cormorants on the Pacific coast of Lower California consists mainly of *Engraulis mordax* Girard, *Sardinops caerulea*, *Anchovia macrolepidota* (Kner and Steindachner), and *Pneumatophorus japonicus diego* (Ayres).

The oceanography of the Gulf of California or Sea of Cortes is inadequately known. Sverdrup (1940), studying the region in February, found a decline in surface temperatures from above 21° C. at the mouth of the gulf to about 15° C. at the latitude of Tiburon Island; the whole northern part of the surface waters of the gulf was at about this temperature. There was clear evidence of upwelling on the eastern side of the gulf off the Bay of Topolobampo and just south of Tiburon Island. The intermediate water is characterized by very low oxygen contents, but at the bottom the oxygen rises again. It is probable that this rise indicates mixture with water sinking in the inner portion of the gulf in winter as a result of evaporation and excess cooling. Vertical mixing of this sort, as well as upwelling determined by winds and currents, accounts for the immense productivity of the gulf. Osorio Tafall (1943) found, in January of 1942, six regions of extreme phytoplankton, namely: (1) around Altamura Island in latitude 25° N.; (2) off the Bay of Topolobampo in latitude 25° 30' N.; (3) off Yavaros in latitude 26° 45' N.; (4) off the Bay of Guaymas in latitude 27° 35' N.; (5) southeast of Tiburon Island in latitude 28° 45' N.; and (6) northwest of Angel de la Guarda Island in latitude 29° 30' N. The second and fifth regions correspond to Sverdrup's stations 23 and 40, which clearly show upwelling. The first, third, and fourth correspond to Sverdrup's stations 11, 24, and 31 (with 32), respectively, which do not give evidence

of upwelling. Sverdrup's station 52 falls in the region of Osorio Tafall's sixth productive area, but there are not enough neighboring stations to indicate the local hydrographic pattern. It is clear from Osorio Tafall's account that transitory meteorological factors play a considerable part in determining the persistence of dense phytoplankton, and it is not improbable that a lengthy investigation would indicate upwelling in all the specially productive areas along the northeastern coast during the dry season when northwest winds tend to blow down the axis of the gulf. It is noteworthy that, although the insulosity of the eastern shore seems little greater than that of the western, the majority of the bird colonies, Georges Island, Patos Island, Pelican Island, San Pedro Nolasco Island, and the Farallon de San Ignacio, lie on the eastern side of the channel. San Pedro Martir lies in mid channel, and only Raza Island and the Roca de la Vela, associated with Angel de la Guarda Island, are on the western side. Certain analogies with the Red Sea during the period of the summer monsoon, when there is a surface current flowing southward down the whole channel, and upwelling along the eastern coast, are obvious. Osorio Tafall indicates that the fisheries are very productive in the gulf and that the chief food of the guano birds consists of *Anchovietta compressa* (Girard), *A. delicatissima* (Girard), *A. helleri* (Hubbs), *Harengula thrissina* (Jordan and Gilbert), *Opisthonema libertate* (Gunther), and *Sardinella stolidifera* (Jordan and Gilbert).

CLIMATOLOGY

Climatically the Pacific coast of the peninsula of Lower California and the littoral of the Gulf of California enclosed by the peninsula appear to differ in certain respects, though they agree in their low rainfall (Page, 1930). The mean monthly temperature on the coast rises from about 13° C. in January to 21° C. in August. Occasional frosts are known. The mean monthly maximum temperatures show little variation from about 26° C. in January to about 31° C. in November. The mean monthly minima follow the monthly mean temperature, about 2.5° in December and January and 12° to 13° C. in July and August. Relative humidity is above 70%, save in November and January; in the

summer months from June to September it reaches or surpasses 80%. In the gulf region the temperature variation is more marked, the highest mean monthly minimum and maximum temperatures occurring in July and August, and the humidity surpassing 50% only in August and December. The whole of the peninsular littoral and most of the eastern coast of the gulf receive less, usually much less, than 250 mm. rain per year, and the mean rainfall for the whole region under consideration appears to be about 70 mm. per annum. In the north of the peninsula this rain occurs mainly in winter, but proceeding southward an increasing proportion falls between May and October, mainly in single days in July, August, and September. The incidence of autumnal rains at the end of the breeding season is clearly an important factor in limiting accumulation of guano.

ORNITHOLOGY

The distribution of the guano birds of the region has been considered recently by Osorio Tafall (1944). On the Pacific coast of Lower California, cormorants, particularly *Phalacrocorax penicillatus* (Brandt), are the most important species. *P. penicillatus* is regarded by Osorio Tafall as the ecological equivalent of the Peruvian guanay. It is a social species, forming dense colonies, and lays on an average four eggs. The chief disadvantage of the species as a guano bird is that it uses a considerable amount of extraneous material, principally *Zostera nana*, but also some brown and red algae, in constructing its nests, thus reducing the purity of the guano. Other cormorants occur along the coast; *P. auritus albociliatus* nests in a large colony with *P. penicillatus* on San Martin Island, but the quantity of extraneous material that it introduces into its nests renders its guano practically worthless. A very important guanera, Isla Pajaros in Magdalena Bay, however, apparently owes its deposit to vast numbers of *P. auritus albociliatus* that flock to it as a resting place but not a breeding site.

Within the Gulf of California the guano birds are different, the higher temperatures apparently favoring boobies rather than cormorants. Vogt (1946) regards all the species present as territorial rather than gregarious. *Sula leucogaster nesiotus* Heller and Snodgrass

is important as a guano bird on an islet off María Cleofa in Las Tres Marias Islands,¹ but within the gulf it is replaced by *S. l. brewsteri* (Gosse) which occurs as far north as Georges Island and forms a large colony, with *S. nebouxi*, at San Pedro Martir. *S. nebouxi* appears to be the chief guano bird on the Farallon de San Ignacio in Topolobampo Bay. *S. sula* subsp., known from the region, nests in bushes and trees and is unlikely to be of any importance.

In addition to these species, *Pelecanus occidentalis californicus* lives on some of the islands, both of the Pacific coast and the gulf, and is apparently not determined in its distribution so strictly by temperature as are the cormorants and boobies. Osorio Tafall specifically mentions a colony on San Pedro Nolasco. There may well be some guano production by various species of terns in the region, but Osorio Tafall evidently regards their contribution as insignificant. Two special cases have also been recorded.

On San Benito Island, *Puffinus opisthomelas* Coues is found filling small caves with guano. On Raza Island, Streets records *Larus heermanni* Cassin as having a colony producing phosphatic guano. This case is perhaps the only one recorded of significant deposits being produced by a gull. As normally gull colonies do not accumulate enough droppings to produce a significant deposit, the record must be regarded as doubtful. Osorio Tafall (1944) regards gulls, notably *L. heermanni* with *L. occidentalis wymani* Dickey and van Rossem on the Pacific coast and *L. o. livens* Dwight within the gulf, as the chief enemies of other sea birds, attacking the eggs and young whenever the colony is disturbed or frightened. This is particularly serious in the cormorant colonies, as the boobies tend to defend their nests better than the cormorants do.

Confirming this general summary of the distribution of guano birds along the Mexican coast, Sr. Carlos H. Benítez, General Manager of the Guaneros y Fertilizantes de Mexico, S. A., most kindly informs me that *P. penicillatus*, *P. auritus albociliatus*, and *Pelecanus*

¹ The brown booby of this colony has been described as *S. l. albiceps* van Rossem, but Wetmore (1939) gives good reason for thinking that it is identical with *nesiotus* from Clipperton Island.

o. californicus, "predominate in the West Coast, and inside the Gulf waters we find" *Sula l. brewsteri* and *Sula nebouxi*.

Vogt (1946) states that Arenas reported 4,895,500 guano birds throughout the region. Of these 1,525,000 were boobies and 2,000,000 were cormorants. He himself suspected the population to be about one-twentieth of that of the Peruvian coast at its peak, i.e., about 500,000 birds.

TOTAL PRODUCTION OF GUANO

Through the kindness of G. W. Beermaker Inc., of San Diego, the following mean values for production and chemical composition of fresh guano between 1918 and 1937 are available:

	TONS PER ANNUM	N	P ₂ O ₅	K ₂ O
Pajaros	250	8%	13%	1%
La Asunción	25	8	9	1
San Roque	50	8	9	2
Maria	50	9	12	2
Chester	45	9	12	2
Elide	175	11	12	2
San Jeronimo	15	8	9	1
Natividad (none after 1928)	50	9	8	2
Various small rocks	5	8	11	2

This makes a total mean annual yield of rather over 615 tons. These estimates do not include any material from inside the gulf.

Guano collection was prohibited by the Mexican government in 1938 and more recently has been resumed by the government-sponsored Guanos y Fertilizantes de Mexico, S. A. Señor Benítez tells me that the annual yield does not exceed 1000 tons, some of this coming from within the gulf, but that it is hoped that with the establishment of an adequate system of wardens and other conservation measures the quantity may be appreciably increased. Considering the fact that G. W. Beermaker, Inc., worked only the western coast of Lower California, while Señor Benítez naturally included the gulf islands in his figure, the two estimates are concordant. Very much higher figures, e.g., Pajaros 1000 metric tons, La Asunción 2000 metric tons, San Jeronimo 400 metric tons, with a total yield for the region of at least 7500 metric tons, given by Dovalina (1928), are obviously erroneous and, though his

localities are all mentioned below, the annual yields given are clearly valueless, for though said to be minimal they seem actually to be from 1.8 to 8.0 times too great.

According to G. W. Beermaker, Inc., "it is our opinion that when the exploitation of this guano was started there could not have been any great accumulated deposit on any island or rock, with the possible exception of Pajaros in Magdalena Bay." This locality, a low, sandy, sheltered island in Magdalena Bay, was used only as a resting place rather than as a breeding site; guano therefore could be collected from it several times a year. The other localities listed by G. W. Beermaker, Inc., are "nesting places, and it is very necessary that the birds should not be disturbed until the young are able to fly and care for themselves. The work on these islands could not be started until August and September. Then it had to be done as fast as possible in order to complete it before the rains began. If the guano became wet its nitrogen value was greatly lowered. Also, heavy rains and high seas would wash all the guano off some of the rocks."

In spite of these conclusions, based on long commercial experience and certainly of general validity, the old analyses of Elide Island guano in the region worked by G. W. Beermaker, Inc., and of guano from Raza Island inside the gulf seem to indicate permanent deposits, while imports to Hamburg in the 1870's from Raza and Georges Islands also provide evidence of substantial old deposits on islands within the gulf. The same conclusion can be drawn for San Pedro Martir and the Farallon de San Ignacio from Krull's (1894) account of these islands. The old deposits on the islands in the gulf seem to have been characterized by the presence of monite, CaHPO₄.

It is, however, clear that the Lower Californian islands can hardly be considered in the same category with those of Peru or the northern South African islands. The total annual production of fresh guano throughout the whole region is less than the annual deposit on a number of single Peruvian islands and of some of the best South African localities. As in the Colonial Islands of the latter country, the guano is nitrogenous mainly by virtue of the fact that it is collected before it

has a chance to lose any great amount of nitrogen. Yet the geographical factors that determine the existence of guano on the South American and South African coasts are certainly also operating on the California coast, though in a modified and less favorable manner.

Comparison with Peru and South Africa is instructive in indicating that although the oceanographic and biological conditions may be quite favorable for a large bird population, relatively small climatic differences may greatly modify the chances of stable deposits persisting. It is interesting that Isla Pajaros, the locality apparently most like those of Peru or South Africa, is situated in the drier part of the coast.

DESCRIPTION OF THE DEPOSITS

SUPPOSED OR ACTUAL GUANO ISLANDS ON THE PACIFIC COAST OF LOWER CALIFORNIA

LOS CORONADOS ISLANDS

LATITUDE 32° 23' N., LONGITUDE 117° 21' W.

Said by Grinnell and Daggett (1903) to exhibit patches of white, indicating the favorite roosting places of sea birds, and to have large colonies of *Pelecanus o. californicus* and *Phalacrocorax penicillatus* and a not quite so numerous colony of *P. a. albociliatus*. Likewise the Soledad Rocks off the southern promontory of Soledad Bay (latitude 31° 35' N., longitude 116° 40' W.) are said in the "Mexico and Central America pilot" (United States Hydrographic Office, 1928a) to be white with "bird lime." In neither case is there any clear evidence of a persistent deposit, and these localities probably should not be regarded as guano islands. Holzschneider indicates a deposit of unascertained nature at San Pedro still farther north. This is almost certainly an error, due to confusion of the San Pedro (latitude 33° 45' N., longitude 118° 20' W.) on the mainland coast of California with the islands of San Pedro Martir or San Pedro Nolasco, to be considered below.

SAN MARTIN

LATITUDE 30° 26' N., LONGITUDE 116° 07' W.

A circular island about 1600 meters in diameter with two peaks, one of which, an

extinct crater, rises to about 155 meters. There is a small lagoon on the southeast side of the island.

The island is frequented by vast numbers of *Phalacrocorax auritus albociliatus*, and a somewhat smaller number of *P. penicillatus*. Wright (1913) estimates that 348,480 pairs of cormorants were nesting in July, 1913. The colony was distributed in a ring around the island, *P. penicillatus* keeping closer to the water than *P. a. albociliatus*. Allowing three young to each nest, about 1,800,000 birds must have been present. A rough examination of the amount of food regurgitated by the young when frightened suggests that half a pound of smelts (probably *Atherinopsis californicus* Girard) and sardines is a conservative estimate of the daily food intake. The entire colony therefore would consume about 400 tons of fish per day. Wright says that on reaching the island the stench of guano was strong, whereas on other islands that he visited the odor was apparent only among the birds. The photographs given of the cormorant colony show the birds occupying whitish patches of bare ground between low bushes. G. W. Beermaker, Inc., report that the island "was supposed to have guano, but evidently the birds had left there before Mr. Beermaker began the work, for we can find no record of guano brought from there." There is thus no certain indication of guano exploitation on the island, though Dovalina lists the island as producing at least 400 metric tons per year, and Holzschneider indicates a nitrogenous deposit on his map.

GERONIMO ISLAND

LATITUDE 29° 46' N., LONGITUDE 115° 51' W.

A barren rock about 8 kilometers from the coast, about 1200 meters long and 500 wide. It rises from cliffs 3 to 6 meters high to a central hill 39.6 meters high. The "Mexico and Central America pilot" (United States Hydrographic Office, 1928a) states that the island is covered in places with a mixture of sand and guano, and the island is mentioned by G. W. Beermaker, Inc. (*in litt.*), as having produced an average of 15 tons per annum, as indicated above.

Rocks 8 kilometers north of Cape Colnett (latitude 30° 57' N., longitude 116° 19' W.)

listed as producing 400 metric tons per annum by Dovalina (1928) must be mentioned as guano-producing localities, although the quantity given is obviously very excessive.

ELIDE OR ADELAIDA ISLAND

LATITUDE 28° 46' N., LONGITUDE 114° 22' W.

A barren rock lying about 1.2 kilometers northwest of Rocky Point, about 400 meters long and 12.2 meters high (pl. 12, fig. 1). The "Mexico and Central America pilot" mentions a thin layer of guano. The island was exploited in the nineteenth century and is still one of the most important sources of Mexican guano. Nesbit (1860) gives four analyses, probably representing material removed early in the history of the exploitation of the island. The first three refer to a poor nitrogenous guano; the fourth must represent interaction with the underlying rock:

	I
H ₂ O	19.60%
Organic	22.25
SiO ₂	7.68
(Al,Fe)PO ₄	—
CaO	18.76
P ₂ O ₅	19.49
CaSO ₄ ·2H ₂ O	—
CaCO ₃	—
Alkaline salts	12.22
N	3.67

The CaO:P₂O₅ ratio for the mean of the first three analyses, for which alone calculation is possible, is 1:0.392. As is indicated on page 126, the modern fresh guano collected from this locality contains about 11% N, a greater proportion than in any of the other guanos analyzed from this coast.

SAN BENITO ISLANDS

LATITUDE 28° 19' N., LONGITUDE 115° 35' W.

Between Guadalupe and Cedros Island, said by Anthony (1900) to have small and inaccessible caves almost filled with guano deposited by a restricted colony of *Puffinus opisthomelas* Coues. Dovalina (1928) lists under Cedros and San Benito, banks and reefs allegedly producing 400 metric tons per annum. This may be the source of Holzschneider's indication of "Echte Guanolager" (i.e., nitrogenous guano deposit) on this island. Frazer (1943) indicates that a good number of elephant seals and sea lions fre-

quent the San Benito Islands. On Guadalupe and on Natividad Islands, where *P. opisthomelas* breeds in burrows of its own construction, Anthony gives no indication of accumulation of guano. *Oceanodroma m. melania* (Bonaparte), *O. monorhinus socorroensis*, and *Halocyptena microsoma* Coues also breed on the island (Bent, 1922; Alexander, 1928) but are not likely to be important guano producers.

ISLANDS OFF POINT SAN EUGENIO

LATITUDE 27° 51' N., LONGITUDE 115° 09' W.

A group of rocks and islands yielding in aggregate at least 170 tons per annum, indicated in the table kindly provided by G. W. Beermaker, Inc., and given above (p. 126). These localities lie in the vicinity of Isla de Cerros and Point San Eugenio, extending a

	II	III	IV
	28.50%	25.00%	6.00%
	34.50	33.00	27.37
	3.60	3.80	25.96
	—	—	13.80
	13.03	14.08	7.78
	13.21	13.95	6.57
	—	—	9.46
	—	—	3.12
	7.16	10.18	—
	6.98	5.71	1.34

little south of the latter, Asunción Island lying at about latitude 27° N.

COLORADO: Off the west coast of Isla de Cerros, about 13.4 meters high (pl. 12, fig. 2).

MARIA ROCK: About 4.6 meters high, between Point San Eugenio and Isla de Cerros (pl. 12, fig. 3).

CHESTER ISLETS: Two rocks 5.5 meters high in the same channel.

NATIVIDAD ISLAND: A larger island, 6 kilometers long and up to 2.4 kilometers wide, rising to 149.7 meters. No guano was produced here after 1928, as when "fishermen were allowed to make camps on the island the birds deserted it."

Two unnamed localities off Porto San Bartolome (latitude 27° 41' N., longitude 114° 53' W.), one of which may be Coffin Rock, mentioned by Dovalina (1928) who lists also Gaviota, Bird and Vela Rocks, all of which appear to lie just south of Porto San Bartolome, in the Bay of San Cristobal.

SAN ROQUE ISLAND: (At latitude 27° 09' N. and longitude 114° 24' W). About 1.2 kilometers long and 15.2 meters high.

ASUNCIÓN ISLAND: Of like length, but reaching an altitude of 50.3 meters.

Though the production of this region is less than that of Isla de Pajaros, and little if any greater than that of Elide, there seems to be a greater concentration of individual bird colonies on this part of the coast than elsewhere along the Pacific littoral of Lower California. The production figures given by Dovalina, namely, 1000 metric tons per annum for Bird, Gaviota, Vela, Coffin, Colorado, and Maria, presumably taken together, 300 metric tons per annum for San Roque and Chester Rocks with associated islets, and 400 metric tons per annum for Adelaida and Natividad are, as has already been indicated, probably quite valueless.

Farther south, the "Mexico and Central America pilot" reports South Whale Island, in San Ignacio Lagoon (latitude 26° 45' N., longitude 113° 51' W.) to be a resort of countless sea birds but mentions no guano.

MAGDALENA BAY

LATITUDE 24° 38' N., LONGITUDE 112° 09' W.

Well known as a resort of sea birds. Bryant (1889), writing of *Phalacrocorax auritus albociliatus* Ridgway, says that the number of birds congregating is "almost incredible"; apparently populations reminiscent of the guanay or the Cape cormorant existed. Isla Pajaros, a low sandy island in the bay, is used as a gathering place for many sea birds, notably these cormorants. The working of a light deposit of guano was said to have prevented breeding at the time Bryant wrote. According to the data given by G. W. Beer-maker, Inc., this is the most important of all the islands on the California Pacific coast, though it is apparently now not used as a breeding place. The total yield of about 250 tons per annum accounts for more than a third of all guano received by this firm in 1918-1937. The photograph (pl. 13, fig. 1) of the sacked guano is an impressive indication of the productivity of the island. In addition to the chemical data given on page 126, Señor Benítez kindly sent the following analysis:

H ₂ O	23.80%
Ignition loss	39.10
N total	6.17
N · NH ₃	2.36
P ₂ O ₅ total	12.87
P ₂ O ₅ available	6.01
Inert matter	18.40

Holzschneider gives Santa Maria on his map in about this position, as having a deposit of uncertain nature. It is possible that this record refers to Pajaros Island, though Santa Maria Bay is just north of Magdalena Bay, from which it is separated by Cape Corso. Maria Island may, however, be intended.

GUANO ISLANDS WITHIN THE GULF OF CALIFORNIA

SAN JORGE OR GEORGES ISLAND

LATITUDE 31° 02' N., LONGITUDE 113° 18' W.

Described in the "Mexico and Central America pilot" as a barren rock about 1.1 kilometers long, rising to a height of 62.8 meters at the southeastern extremity and lying 11 kilometers from the eastern shore of the Gulf of California. Bent (1922) states *Sula leucogaster brewsteri* breeds here. Fraser (1943) says the island is white with guano, and that a colony of *Larus heermanni* Cassin occupies an ancient alluvial fan above the shore line. This colony is well shown in Fraser's photographs. Heiden (1887) reports that 1700 tons of guano were brought to the port of Hamburg in 1876 from this island. An analysis by E. Güssefeld, published by Ullmann (1906) records merely 37.71% P₂O₅ and 1.50% Fe₂O₃.

CONSAG [SIC] ROCK

LATITUDE 31° 07' N., LONGITUDE 114° 29' W.

Presumably the Consagra Rock of Dovalina (1928), said in the "Mexico and Central America pilot (west coast)" to be 87.2 meters high and covered with guano. A fine photograph of this rock is given by Fraser (1943).

PATOS ISLAND

LATITUDE 29° 16' N., LONGITUDE 112° 29' W.

A small islet just north of Tiburon Island, low except on the northwest side where it rises to a height of 83.5 meters, said ("Mexico

and Central America pilot," 1928a) to be whitish with guano. It was commercially exploited in the nineteenth century and still yields guano (A. A. Lelevier, *vide* G. W. Beer-maker, Inc., *in litt.*). Old analyses by Nesbit (1860) and Voelcker (1876) exist. It is possible that the record for Tiburon Island on Holzschneider's map refers to Patos Island, which he does not otherwise indicate. Dovalina (1928) gives a record for Angel de la Guarda, a large island farther to the west, as producing with Consagra Rock 900 metric tons per annum.

One of Nesbit's analyses of Patos material refers to a poor nitrogenous guano like that of Elide:

	NESBIT, I
H ₂ O	26.86%
Organic	32.45
SiO ₂	2.55
CaO	14.87
P ₂ O ₅	15.95
Alkalis	7.38
N	5.92

The CaO:P₂O₅ ratio is 1:0.424.

The other analyses given by Nesbit and the analysis given by Voelcker must refer to more leached material, evidently mixed with sand; possibly they came from a deeper part of the deposit. Reference of part of the phosphate to (Al,Fe)PO₄ may be arbitrary in Nesbit's analyses, but such phosphate must have occurred at least in his analysis II. It is not possible to recalculate these analyses accurately on the basis of oxides, and they are therefore given as originally recorded:

	NESBIT, II	NESBIT, III	VOELCKER
H ₂ O	8.80%	12.20%	14.35%
Organic	10.67	8.61	—
SiO ₂ or insol.	21.28	14.40	14.72
(Al,Fe) ₂ O ₃	—	1.17	—
(Al,Fe)PO ₄	4.45	1.57	—
Ca ₃ P ₂ O ₈	50.00	50.98	53.48
Mg ₃ P ₂ O ₈	—	0.94	
Alk. salts	0.73	0.90	4.63
CaCO ₃	—	—	2.58
CaSO ₄ ·2H ₂ O	4.07	9.23	—
N	0.85	0.81	0.96

RAZA OR RASA ISLAND

LATITUDE 28° 50' N., LONGITUDE 113° 01' W.

Lying off the west coast of the Gulf of California, south of Angel de la Guarda Island, described by Streets (1877b) as a small

low island; it is about 1.2 kilometers long and 0.8 kilometer wide. The island is entirely destitute of vegetation, but was occupied by an immense colony of *Larus heermanni*, Streets estimating "without exaggeration . . . a bird on every square foot of the ground, and others were continually hovering about overhead." The whole surface of the island was said to have been covered with a thick layer "composed largely of a tri-basic phosphate." Streets thought this was due to interaction of bird droppings and the underlying "black volcanic rock." He indicates that on breaking open boulders a sharp line of demarcation between the phosphate and the unaltered rock is observed and that as the phosphate is softer than the original rock it is easily worn off by the attrition of the birds' feet, so smoothing off the inequalities of the island. In spite of this account, the attribution of the guano to *Larus heermanni* must be regarded as questionable. Ten thousand tons, of an estimated 70,000, had been removed in 1875. These high estimates receive some confirmation from Heiden's (1887) report that in 1874-1877, no less than 13,530 tons of Raza Island phosphatic guano were received at the port of Hamburg. Voelcker (1876) and Voigt (*in* Heiden, 1887, analysis made in 1874) give analyses; three of Voelcker's (II, III, and IV) seem to show some influence of the underlying rock. A more modern partial analysis, kindly sent by Señor Benítez of Guaneros y Fertilizantes de Mexico, S. A., is also available. These analyses are set out in table 11.

Voigt gives 0.46% of his silica as SiO₂ and 4.84% as sand. Voelcker considers his samples II and IV represent crust guano. Voigt's sample is chemically similar to these; he states 0.51% P₂O₅ to be soluble. The modern analysis sent by Señor Benítez gives 4.40% "available" P₂O₅. The CaO:P₂O₅ ratio for Voelcker's analysis I, corrected for carbonate, is 1:0.367; a small amount of magnesium and ferric phosphate may have been present. Voigt's analysis, assuming all the sulphate present as CaSO₄, gives a ratio 1:0.482; a little magnesium phosphate may have been present, but a large part of Voigt's sample apparently consisted of calcium monohydrogen phosphate, presumably as monetite, CaHPO₄. If all the phosphate were present as monetite, it would require 5.04% H₂O; if as brushite, 25.2% H₂O, which is obviously

TABLE 11

	Voelcker				Voigt	Guanos y Fer-tilizantes
	I	II	III	IV		
H ₂ O	4.83%	1.30%	3.70%	12.34%	4.08%	12.86%
Organic and combined H ₂ O	12.72	9.80	11.13	—	9.26	12.00
N	1.04	0.37	0.86	—	0.40	0.80
CaO	37.36	37.21	34.07	36.57	35.28	—
MgO	1.76	—	—	—	1.18	—
Fe ₂ O ₃	0.50	—	—	—	1.14	—
Al ₂ O ₃	0.81	7.18	9.54	8.71	—	—
Alkali salts	5.54	—	—	—	—	—
CO ₂	0.46	—	—	—	—	—
SO ₃	—	—	—	—	4.03	—
P ₂ O ₅	34.33	40.31	34.81	38.35	39.70	21.95
Insol. or SiO ₂	1.69	4.20	6.75	4.03	5.30	10.97

impossible. Voelcker's crust guanos II and IV also may well have contained monetite. Krull (1894) states that the rocks of the island are covered with the same hard phosphatic guano that he observed at San Pedro Martir, where again monetite was probably the chief constituent.

SAN PEDRO MARTIR

LATITUDE 28° 23' N., LONGITUDE 112° 20' W.

A rock about 2.4 kilometers long, rising to a height of 319 meters, set near the middle of the Gulf of California. Goss (1888) reports that the San Francisco Phosphate and Sulphur Company maintained a force of about 135 Yaqui Indians on the island to collect the guano, which formed a crust 1 to 4 inches (ca. 2.5–10 cm.) in thickness over the rocks. The exploitation had been going on for three years at the time of his visit, and it was estimated that the material would be exhausted after six or eight years' further work. Guano, doubtless newly deposited, is, however, still obtained (A. A. Lelevier, *vide* G. W. Beer-maker, Inc., *in litt.*). The process of collecting guano had doubtless greatly disturbed the birds; at the time of Goss' visit a conservative estimate of the breeding population gave:

<i>Sula nebouxi</i> (sub <i>S. gossi</i>)	1000
<i>S. l. brewsteri</i>	700
<i>Phaeton rubricauda</i>	80
(<i>Corvus corax sinuatus</i>)	100)
<i>Larus occidentalis</i>	a few

Sula nebouxi preferred smooth, bare rock,

such as rock surfaces newly cleared of guano, on which to deposit its egg; no attempt at a nest was made. *S. l. brewsteri* constructed a more definite nest of a few sticks, seaweed, or feathers, mostly on ledges or in niches of the rock. Goss considered that when undisturbed the island would contain "thousands and thousands" of boobies at the breeding season.

Krull (1894), who apparently visited the Gulf of California, gives an account of the deposits on San Pedro Martir. He regarded this island, Raza, and the Farallon de San Ignacio as the three most important guano islands in the gulf. He states that the island is cut by 14 ravines, of which three are large, and that numerous sea caves occur in the cliffs. The slopes and sides of the ravines were covered with guano. The material occurred as thick crusts, reef, and columnar flows ("escollos i aun chorros columnares"), was dark gray, full of cracks, and rested in general on a dark yellowish, powdery guano, mixed with sand, ripio, ferric phosphate, and gypsum. These impurities and the humidity of the material increased with depth. This powdery material was more abundant on the floors of the ravines.

The phosphate contents of the purest parts of these deposits appear to have been very high:

	P ₂ O ₅
Rugose yellow reef	38%
Conchoidal dark mass	40
Grayish yellow crust	45
Grayish brown flow	41
White bed	44

A sample of the densest material, described as hard guano or rock phosphate gave:

P ₂ O ₅	48.95%
(Ca,Mg)O	38.62
H ₂ O	12.41

The magnesium was unfortunately regarded as replacing calcium, and the material apparently regarded as CaHPO₄·H₂O, which is not known as a homogeneous material. Presumably a considerable part of this dense guano consisted of monetite, CaHPO₄, though some brushite, CaHPO₄·2H₂O, may have been present. It is of course by no means certain that all the water recorded in Krull's analysis is essential. Guano from the north side of the island is said to have consisted of:

Calcium phosphate	53.0%
(Al,Fe)PO ₄	14.4
Calcium sulphate	10.5
Insol. rock	9.1
H ₂ O	12.6

A clay-like guano occurred in some of the caves on the slopes and ravines of the island. At least the surface of this material was very richly nitrogenous, containing 19% to 22% nitrogen and but 31% ash. Deeper down the cave the guano was damper, contained but 6% to 8% nitrogen, 55% ash, and 21% to 25% P₂O₅.

SAN PEDRO NOLASCO

LATITUDE 27° 55' N., LONGITUDE 111° 23' W.

Described in the "Mexico and Central America pilot" as a barren rock of volcanic origin, about 3.6 kilometers long, 1.2 kilometers wide, and rising to a height of 326.4 meters. The same authority states that some deposits of guano are said to exist on the island. San Pedro Nolasco is shown in photographs given by Fraser (1943), which indicate a few bushes and other vegetation. Fraser says that the chief birds are pelicans and Brewster's boobies.

FARALLON DE SAN IGNACIO

LATITUDE 25° 26' N., LONGITUDE 109° 24' W.

Near the entrance to Topolobampo Bay, shown by Fraser (1943), whose photograph is here reproduced (pl. 13, fig. 2), as a flat-topped, steep-sided island. Krull (1894) indi-

cates that it is about 490 meters long and 137 meters high. It is said to be the home of thousands of sea birds, including tropic birds and *Sula leucogaster brewsteri*, a species that is doubtless the most important producer of guano inhabiting the island. Krull says that the guano occurred as fragments of crust often of large size and curiously twisted, lying over a yellowish brown powder 6 to 8 inches thick which consisted half of insoluble residue, contained 10% available P₂O₅ as well as ferric phosphate and gypsum. An analysis of the hard guano suggests that it consisted largely of monetite and brushite:

H ₂ O	13.4%
CaO	33.8
MgO	2.0
P ₂ O ₅	36.8
SO ₃	10.0
Insol.	4.0

If all the sulphate is present as gypsum, as Krull assumes, the phosphatic material would consist of:

H ₂ O	11.9%
CaO	36.0
MgO	2.7
P ₂ O ₅	49.4

A second similar analysis is given, but it is not quite clear that it refers to this locality.

ISLA GAVIOTAS

LATITUDE 24° 17' N., LONGITUDE 110° 19' W.

A small island about 400 meters long and 274 meters high, in La Paz Bay. It is said in the "Mexico and Central America pilot" to have a whitish color owing to a light deposit of guano. It is now regarded as an important guano island. Señor Benítez sends the following analysis:

H ₂ O	18.54%
Ign. loss	41.80
N total	3.14
N·NH ₃	1.79
P ₂ O ₅ total	21.90
P ₂ O ₅ available	3.62
Inert	1.83

This may be the locality producing guano of unspecified nature, indicated by Holzschneider near Cape San Lucas, the southern extremity of Lower California.

GUANO SOUTH OF THE LOWER
CALIFORNIA PENINSULA

LAS TRES MARIAS ISLANDS

LATITUDE 21° 16' N., LONGITUDE 106° 19' W.

An islet known to Bailey (1906) as White Rock, described as lying between Maria Magdalena and Maria Cleofa Islands. The position of the White Rock as given in the description of these islands in the "Mexico and Central America pilot" is different. The islet is about 61 meters high with a nearly flat top. Bailey found a fine colony of *Sula leucogaster nesiotes* (sub *brewsteri*) breeding on this high level plateau, though at the time of his visit it was much disturbed by men collecting "the guano from this countless flock of birds which had probably been breeding there for centuries." Nelson (1899) also describes a colony of brown boobies, presumably at the same locality as was visited by Bailey. He says that in the heat of the day the birds do not incubate but stand shading the eggs or chicks. The island had a breeding colony of *Phaeton aethereus* and probably other species which are unlikely to be of significance in guano production.

Bailey states that Mr. George Beermaker, then of the Union Fertilizer Company¹ of Los Angeles, examined Isabella Island between Las Tres Marias and the coast for guano, but with what result is not indicated. Holzschneider gives Isabella on his map as the site of a phosphatic guano deposit. Isabella has colonies of *Sula dactylatra* and *Sterna fuscata*, and Bailey believed *S. l. nesiotes* was establishing itself on the island as the result of the disturbance of its home on White Rock. Bailey also mentions that the brown booby roosted but did not breed on Piedra Blanca off San Blas. Of two rocks of this name given in the "Mexico and Central America pilot," Piedra Blanca del Mar is presumably meant. Of all the localities in this region only Bailey's White Rock off Maria Cleofa in Las Tres Marias can be regarded as

a well-established guano island, and this seems to have been the site of the only important breeding colony of *S. l. nesiotes* on this part of the Mexican coast. Dovalina (1928), however, indicates that islands, banks and reefs along the coasts of Nayarit, Jalisco, and Colima, i.e., from about latitudes 18° N. to 22° 30' N. produced 500 metric tons per annum. In view of his exaggerated estimates the figure given probably indicates very little guano deposition. It is possible that the unspecified localities mentioned actually include White Rock off Maria Cleofa. At the extreme southern end of the stretch of coast indicated, the White Friars or Potosi Rocks, a group of 12 rocks and islets, are said by Fraser to be the nesting sites of a variety of marine birds and to be covered by guano which makes them recognizably white against the darker shore line, particularly when approached from the south. Fraser gives a good photograph.

POSSIBLE INLAND GUANO IN NEVADA,
UNITED STATES

A single rather doubtful case, having some remote analogy to the inland deposits of the Atacama Desert, is best mentioned in this place. Gale (1912) has described the niter claims near Lovelock, Nevada. At a locality above the Upper Humboldt Lake, known as the Queen Place Claim, soluble salts consisting mainly of nitratite (NaNO_2) have been discovered in rock shelters; two analyses gave:

Insol.	30.89%	4.00%
NO_3	35.65	53.12
Na	20.20	26.26
K	tr.	tr.
Cl	10.90	8.83
SO_3	tr.	1.33
CaO	sl. tr.	0.53

It is supposed that the nitrate of this region represents the results of oxidation of ammonia leached from guano deposited by bird colonies that occupied a headland projecting into the Pleistocene Lake Lahontan. The sodium is probably derived from the water of the lake.

¹ Father of the present Mr. G. W. Beermaker of G. W. Beermaker, Inc., of San Diego, the source of so much valuable information on this region.

THE SOUTHWEST AFRICAN GUANO COAST

The closest analogy to the Peruvian guano coast is provided by the corresponding southwestern coast of Africa. The chief differences between the two regions are primarily of physiographic origin. The African continent projects less far towards the Antarctic Ocean than does South America, and it possesses no high coastal mountain range corresponding to the Andes. The modification of the planetary wind pattern by local large-scale topography is thus less extreme on the African coast than on the South American. The same general oceanographic and climatological peculiarities develop on both coasts, but they are evidently a little less constant and a little less striking on the southwest African, than on the western South American, littoral.

The southwest African guano coast may be regarded as extending from latitude 22° S. southward to the Cape of Good Hope. Seal Island in False Bay, Dyer's Island on the Bredasdorp coast, and Bird Island in Algoa Bay yield some guano, and though their surroundings are oceanographically very different from those of the other islands it is inconvenient to treat these islands separately.

There are some unsatisfactory records indicating the occurrence of guano farther north than latitude 22° S. Stutzer (*in* Stutzer and Wetzel, 1932)¹ states that small deposits have been found on an island in Santa Maria Bay (latitude 13° 25' S., longitude 12° 33' E.); at Coroca just north of, and at Sacco de Baleia south of, Port Alexander (latitude 15° 48' S., longitude 11° 48' E.); at Rocha de Pinda, a locality which it has not been possible to identify; at Tiger Bay (latitude 16° 45' S., longitude 11° 48' E.); and on an island at the mouth of the Kunene River (latitude 17° 18' S., longitude 11° 46' E.)—all localities being on the coast of Angola. Meise (1938) quotes from Bolle (1855) a record for a locality named Rio Bembaruque, which may lie in latitude 15° 45' S., or in latitude 16° 25' S. There is nothing inherently improbable in the occurrence of guano on the southern

coast of Angola or in the northern part of the coast of southwest Africa, where deposits have been indefinitely indicated between latitudes 17° S. and 21° S. The most northerly well-established locality would seem to be 20 kilometers south of Cape Cross Bay (latitude 21° 47' S., longitude 15° 57' E.) where a deposit, apparently interstratified with salt, is said by Schultze to consist of old guano in the now dry Sierra Bay and by Haughton (1933) to occur on the small islands in a lagoon. This deposit was exploited by the Damaraland Guano Company after 1895 (Schultze, 1907). An analysis of such Damaraland guano (Ullmann, 1906) indicates it to have been nitrogenous, while the fact that 6000 to 8500 tons were annually exported for some years shows that the deposit was extensive. The report of the Superintendent of the Government Guano Islands (Zeederberg, 1919) mentions 4000 tons of Cape Cross phosphate being acquired for sale in South Africa. It appears therefore that part of the deposit was not nitrogenous. The "Sailing directions for the southwest coast of Africa" (United States Hydrographic Office, 1932a) indicate that the settlement exporting guano still existed when the work was compiled, and that some recent guano is collected at Bird Rock in Walvis Bay (latitude 27° 54' S., longitude 14° 26' E.). This last locality, according to Schultze, produces less than 1 ton per year, but it seems likely that St. Croix Island, referred to in 1944 by the superintendent of the islands (*in litt.*) as housing an increasing bird population, refers to the Cape Cross locality. The majority of the deposits lay farther south; many birds frequenting Walvis Bay when not breeding certainly breed on the islands farther southward down the coast. Most of the guano deposits are insular as in Peru, though Range indicates small coastal accumulations in Hottentots Bay (latitude 26° 08' S., longitude 14° 57' E.).

The guano islands of South West and South Africa are now worked for newly deposited guano by the government of the Union of South Africa, in a manner comparable to that employed by the Peruvian authorities. For administrative purposes, no less than

¹ Stutzer gives as authority a reference to Lacroix (1918), a work having nothing to do with this part of the African coast.

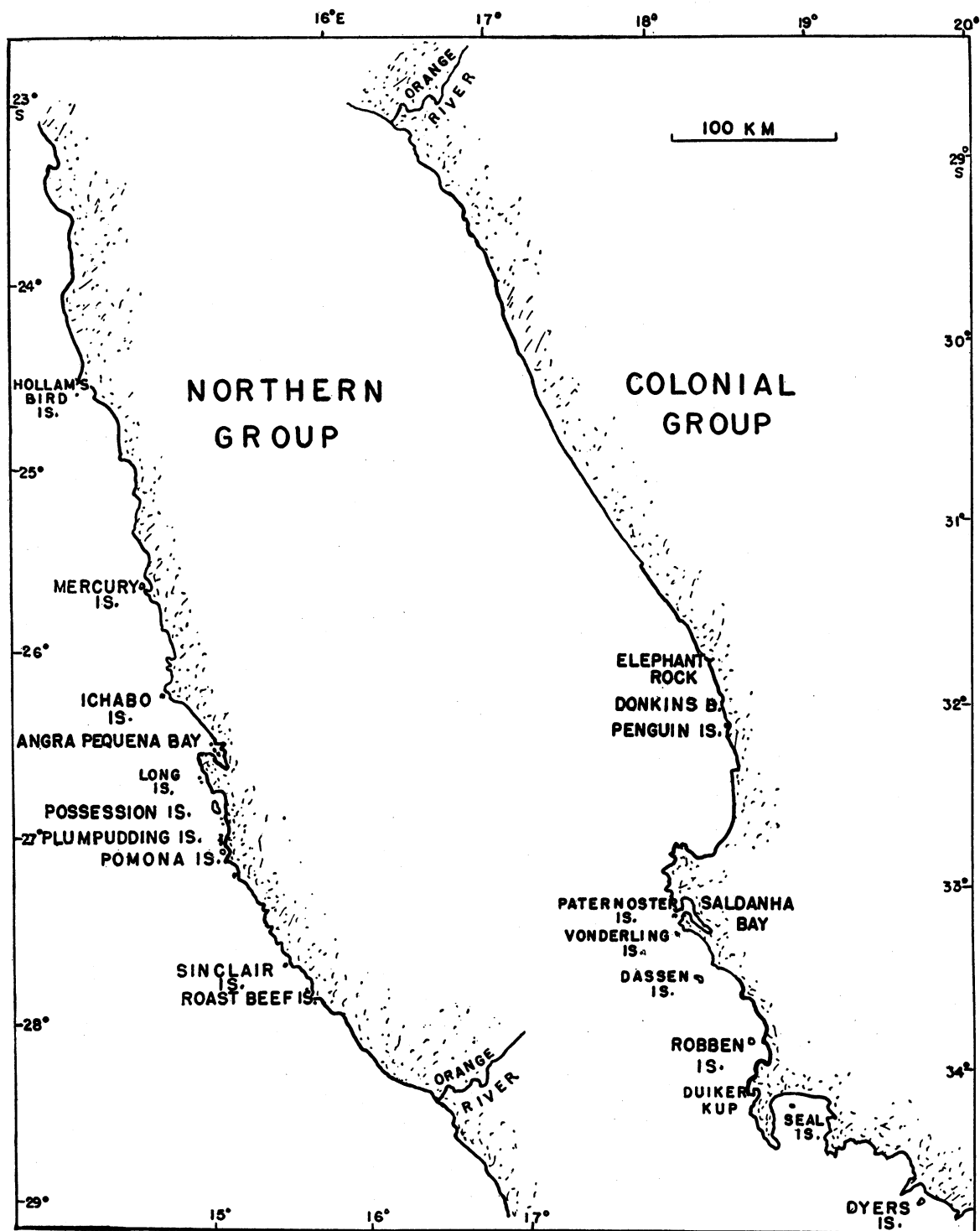


FIG. 36. Map of the southwestern coast of Africa to indicate position of Government Guano Islands.

geographically and biogeochemically, they are separated into the Northern group along the coast of South West Africa, and the Colonial group along the coast of the Cape of Good Hope (fig. 36).

CLIMATOLOGY

The prevailing winds, at least off shore, follow the coast line and form the eastern part of the general circulation system around the high pressure area of the South Atlantic. A western component is, however, well marked, at least locally, though the trend of the coast line is in general north-northwest to south-southeast. The prevailing wind at Walvis Bay, just north of the northernmost guano islands, is southwest. Reversals are evidently common, particularly in summer; from September to February the data given in the "Sailing directions for the southwest coast of Africa" (United States Hydrographic Office, 1932a) indicate a north wind at Walvis Bay on about one-fifth of the occasions of observation. The rainfall is very low at the latitudes of the northern guano islands. At Swakopmund (latitude 22° 40' S.) and Walvis Bay (latitude 27° 54' S.) just north of the northernmost island the mean annual precipitation is 15.2 mm. At Alexander Bay, just south of the southernmost of the Northern group of guano islands, the rainfall is somewhat greater, the mean annual fall being 55 mm. The precipitation on all the Northern group of islands presumably lies between the limits set by the Walvis Bay and Alexander Bay figures, the northernmost islands probably receiving about 20 mm. per annum, the southernmost islands about 50 mm. per annum. In spite of the low precipitation, fog is frequent on the coast, and the relative humidity is high. At Walvis Bay the mean monthly value of the relative humidity varies from 86% in September to 77% in July. All months save the latter have mean values of at least 80%. The mean monthly temperature varies from 14.3° C. in August to 18.9° C. in February and March, but the early winter months (April to July) are characterized by both the minimum (2.2° C.) and maximum (41.7° C.) temperatures. The thermal regime at Port Nolloth (latitude 29° 14' S.) is essentially similar, though all temperatures are somewhat lower, the monthly

means varying from 12.2° C. in July and August to 15.6° C. in December, January, and February. The extremes occur between April and December, varying from 0° C. to 40° C. The whole Northern group of islands presumably experiences temperatures intermediate between those of Walvis Bay and Port Nolloth. The rainfall of the west coast south of Port Nolloth increases on proceeding from north to south. The isohyet for 127 mm. (5 inches) cuts the coast at latitude 31° 50' S. (Lewis, 1938) and that for 254 mm. (10 inches) at latitude 32° 40' S. on the east side of St. Helena Bay.

Records for stations on three of the Colonial Islands are available (Lewis, 1938):

	MM. PER ANNUM
Dassen Island	338
Robben Island	438
Bird Island, Algoa Bay	476

From the general distribution of rainfall and from these specific records, it would appear that, apart from the four islands north of Saldanha Bay (Elephant Rock, Penguin Island, Paternoster Island, and Jacob Reef), the rainfall on all the Colonial Islands lies between 250 mm. and 476 mm. per annum, or more than five times that of the wettest of the Northern Islands. Dassen Island and Robben Island have a rather marked seasonal distribution of their rainfall, over 70% of which falls in the five winter months from May to September. The rainfall of Bird Island is much more evenly distributed.

OCEANOGRAPHY

The extreme eastern limb of the South Atlantic Gyral forms the Benguela Current, which is the Atlantic analogue of the Peru Current. Intense upwelling occurs on the coastal side of the Benguela Current. The temperature maps prepared by Bönecke (1936) indicate that the mean monthly temperature of the coastal water never exceeds 16° C. over the stretch of coast line between latitudes 23° S. and 33° S. and is always below 20° C. throughout the whole of the southwest African littoral from latitude 17° S. to the Cape of Good Hope. The boundary between the cold water of the Benguela Current and the warm water of the Agulhas Current in

the neighborhood of the Cape Peninsula is exceedingly sharp.

At the northern end of the Benguela Current, reversal of flow appears to occur frequently as a normal event at all times of year. Schott (1931) gives the following summary of the percentage incidence of direction recorded in observations made at sea:

LATITUDE	CURRENT TO NORTH AND WEST		CURRENT TO SOUTH AND EAST		NO CURRENT	
	Feb.-Mar.	Aug.-Sept.	Feb.-Mar.	Aug.-Sept.	Feb.-Mar.	Aug.-Sept.
4°N.- 2°N.	33	34	53	53	14	13
2°N.- 0°	56	44	31	34	13	22
0° - 2°S.	60	44	27	37	13	19
2°S - 4°S.	59	64	28	28	13	8
4°S.- 7°S.	72	74	22	20	6	6
7°S.-10°S.	61	56	25	24	14	20
10°S.-14°S.	51	57	35	38	14	5

It would appear that on about a quarter or a third of the occasions of observation, both in the late winter as well as in the late summer, a warm counter current can be detected in the northern part of the region. Unfortunately there is no information relating to a possible correlation with reversals in the direction of the wind.

The incidence of upwelling, and its chemical and biological consequences, are well shown on the map (fig. 37) from Bönecke (1936) for the divergence of the temperature from the latitudinal mean of the Atlantic Ocean, that of Hentschel and Wattenberg (1930) (fig. 38) for the surface phosphate, and that of Hentschel (1933) (fig. 39) for the total plankton. The maps for the temperature anomaly and for the distribution of phosphate indicate that the major center of upwelling is at about latitude 23° S. The northernmost guano islands of importance lie a little to the south of this, but the whole group of Northern Islands is within an area markedly enriched in phosphate, while all of the southern islands off the west coast of South Africa are surrounded by water that is richer in phosphate than is the average Atlantic water. The plankton map indicates very great productivity from latitude 25° S. northward and also local centers of high productivity in about latitude 28° S. and more markedly about latitudes 33° to 34° S. The productive area about latitudes 33° to 34° S. surrounds many of the important Colonial Islands. Dark water, due to immense popu-

lations of diatoms, is well known to fishermen on this part of the coast and is supposed to indicate local aggregation of fish (Gilchrist, 1914a).

It is very probable that if a more detailed study of temperature and phosphate concentration were made, local centers of upwelling

corresponding to these more southerly productive zones would be discovered. The coastal water of the Benguela Current would in fact probably be found to have a structure analogous to that of the Peru Coastal Current or the California Current, in which interdigitating tongues of cold upwelled water and warm water of superficial origin form a series of anticyclonic swirls.

The fisheries of the Benguela Current region are rich, but little statistical matter seems to be available as to their output and its variations. The small fish, which are repeatedly mentioned in the reports of the Superintendent of the Government Guano Islands, are presumably mainly sardines, *Sardina sagax* (Jenyns).

The rather frequent observations of a southward flowing counter current, in the northern part of the course of the Benguela Current, have already been mentioned. The possibility of catastrophic biological effects of the influx of warm water into the normally cool region of the southwest African coast seems to have been little considered, though there are certain fairly well-known phenomena to be met with on that coast that strongly suggest aguaje, and very great variations in the food supply of the guano birds, suggestive of the periodic variations off Peru, have also been noted. The variations in the supply of the fishes eaten by the birds are discussed in the next section, but some account of the phenomena reminiscent of aguaje is appropriate in the present context.

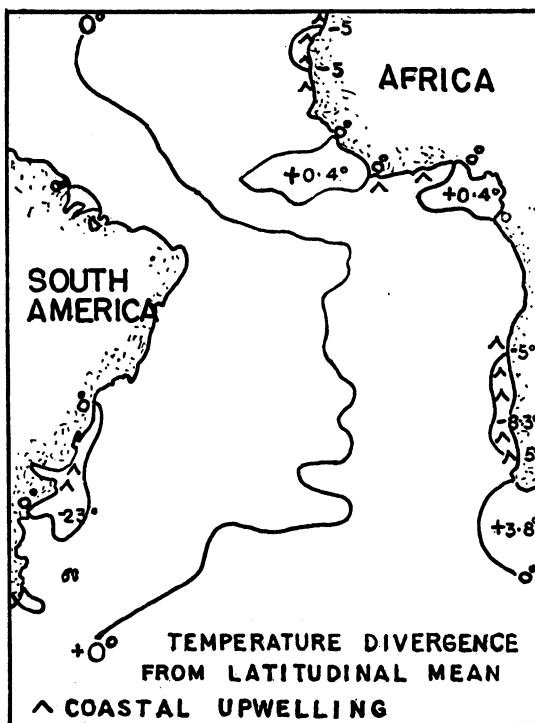


FIG. 37. Central and South Atlantic, divergence of temperature from latitudinal mean. After Bönecke.

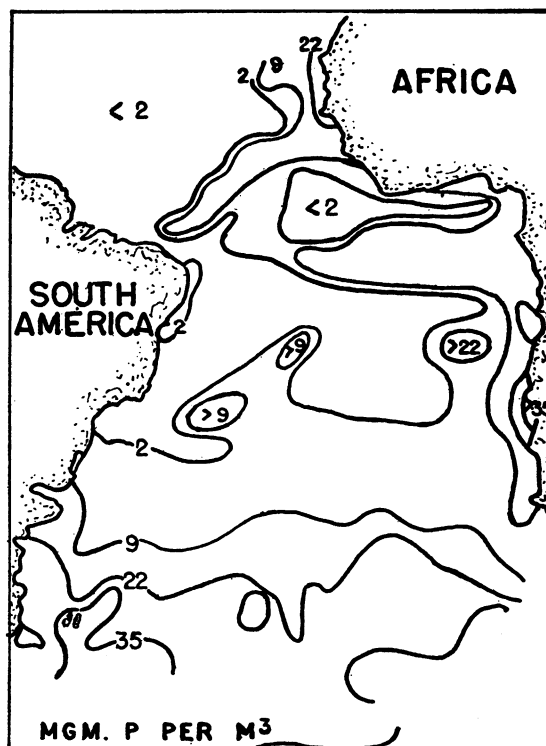


FIG. 38. Central and South Atlantic, soluble phosphate phosphorus. After Hentschel and Wattenberg.

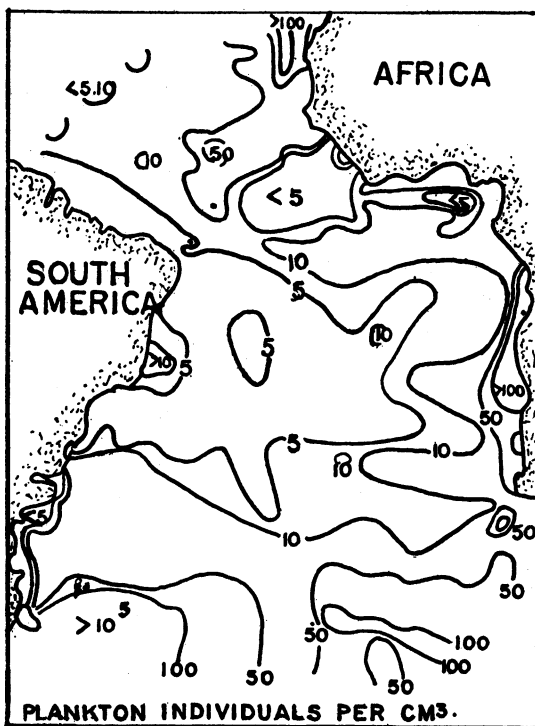


FIG. 39. Central and South Atlantic, total plankton. After Hentschel.

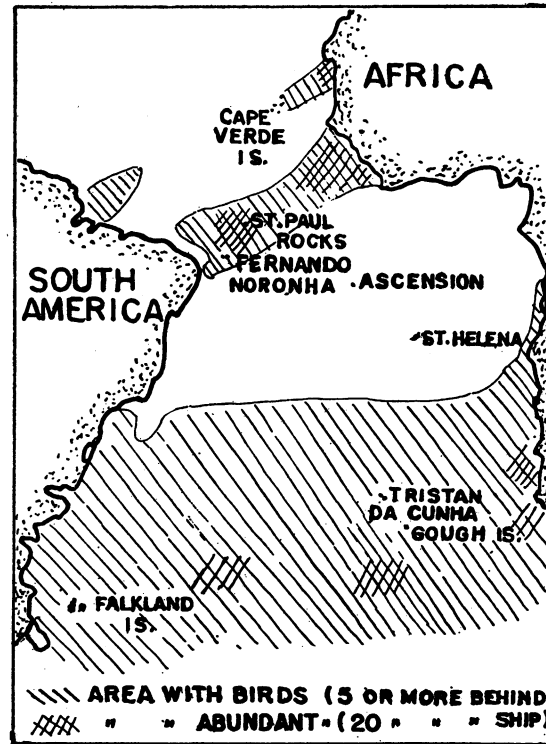


FIG. 40. Central and South Atlantic, relative density of avifauna. After Hentschel.

Marchand (1928) found that a band of green mud extends from latitude $21^{\circ} 30' S.$ southward along the coast to about latitude $24^{\circ} 30' S.$, or to just north of the important guano islands. This mud appears to be sterile and to contain H_2S . It is bounded on its western side by the 80-fathom isobath. Within the green mud zone there is a shorter littoral area free from sulphides and supporting a rich benthic biota. Specimens of the green mud from Walvis Bay contain, when not contaminated with sand, about 60% insoluble inorganic matter, and virtually the whole of this represents the frustules of diatoms (Copenhagen, 1934). It is probable, as Copenhagen suggests, that the green mud is formed as the result of the excessive productivity of the upwelling zone and some local hydrographic peculiarity which leads to a very reduced movement of water over the bottom in the area covered by the green mud. It would be perhaps easier to understand the production of the deposit if it were assumed that rather frequent mass mortality of plankton occurs over the green mud area.

Spectacular mortality of fishes is recorded in various places along the south and southwest African coast and has been discussed by Gilchrist (1914a). On the southern coast of South Africa there is evidence that this mortality is due to abnormal upwelling of cold water. The phenomenon apparently occurs annually at Knysna and much less frequently at certain other localities. Gilchrist unfortunately does not distinguish between such mortality and the mortality on the west coast, which is more likely to be due to influx of warm oceanic water than an accentuation of cold upwelling which is here a normal event. The occurrence of mass mortality around the Cape Peninsula was first recorded according to Gilchrist, in 1837, when it was observed all around Cape Point and when a number of dead whales were washed up. Two or three times in each summer, red water, said by Gilchrist to be due to *Noctiluca*, is observed in False Bay, and the same phenomenon has been observed in Saldanha Bay, as in 1904, and in Stumpnose Bay, which acquired a dark red color in 1869. Fish deaths accompanied these last two occurrences. Vast mass mortality of fishes occurs frequently in Walvis Bay; Gilchrist implies

that it is an annual event but quotes accounts of particularly extreme cases, the first in 1881, the second in 1887, the third said to have occurred in 1883, perhaps a misprint for 1893. Before the first occasion a number of small lamellibranch mollusks of a kind never before noted on the beach were cast up, and eels, not previously obtained at Walvis Bay, were caught by native fishermen. This suggests some marked hydrographic disturbance. According to Classen (1930) the fish mortality is observed with considerable regularity at some time during every summer (December–February). It is usually attributed to local conditions, such as sulphur springs or volcanic disturbances. It is, however, clear, as Kaiser (1930) points out, that the suggested causes are inadequate, and that peculiarities in the sediments, geography, and hydrography of the region must be involved. The fish deaths are associated with production of sulphide, which may discolor shipping and is reminiscent of the Callao Painter. It is unfortunate that no adequate hydrographic information seems to exist permitting a true evaluation of the similarity of the phenomena on the coast of southwest Africa and the various aspects of El Niño and agüaje off Peru. The available data at least indicate that a more extended investigation would be interesting.¹

ORNITHOLOGY

The relative density of the bird population of the ocean off the western coast of Africa can be estimated from the map (fig. 40) based on observations made on board the "Meteor," and published by Hentschel (1933). The observations in the regions now under consideration were made during July and August, out of the main breeding season, north of latitude $30^{\circ} S.$, and in November and December, or during the beginning of the main breeding season, south of latitude $30^{\circ} S.$ The map shows a clearly marked concentration along the coast, with a center of maximum abundance at about latitude $21^{\circ} S.$ and another between latitudes $30^{\circ} S.$ and $40^{\circ} S.$ The ill-defined minimum between these two centers might perhaps be less marked if all the observations had been made in November

¹ Since the above was written, a very important paper by Brongersma-Sanders (1948), discussing the mass mortality of fish at Walvis Bay, has appeared.

when some of the birds observed around Walvis Bay would probably have moved a little southward to breed on the islands of the Northern group. It is, however, reasonable that the bird population should follow the general pattern of productivity, with at least two centers corresponding to the regions of maximum phytoplankton production, one from latitude 25° S. northward, the other around latitudes 33° and 34° S. The map of the bird populations at least seems to confirm this prior expectation. The three most important species of guano birds on the western South African coast are the Cape gannet or malagas, *Morus capensis* (Lichtenstein), the Cape penguin, *Spheniscus demersus* (Linnaeus), and the trek duiker, *Phalacrocorax capensis* (Sparrman). Minor contributions to the deposits are also probably made by other cormorants, *P. carbo lucidus* (Lichtenstein), *P. neglectus* (Wahlberg), and *P. a. africanus* (Gmelin). *Morus capensis* is at present probably the most important of the three main guano birds, as it is the chief species inhabiting Ichabo Island, the most productive of the Northern Islands, and also has immense colonies on Malagas Island in Saldanha Bay and on Bird Island in Algoa Bay. Speight estimated the Ichabo colony as composed during the breeding season, from September to March, of about 6,000,000 birds. The Cape gannet also breeds or has bred on Hollam's Bird Island, Mercury Island, Possession Island, and Halifax Island (Andersson, 1872; Meise, 1938), though of these Speight mentions only the first as having a population of malagas at the present time. It is clear that while the other two main guano birds are more widely distributed than the gannet, the particularly favorable nature of the islands that have gannet colonies makes this species the most important of the three. Hewitt (1938) indicates that it is less subject to disturbance and to the unfavorable results of periodic variations in food supply than are the other two species. It is certain that since the removal of the original guano cap, *Morus capensis* has increased on Ichabo Island, and by the time that Andersson (1872) wrote, it already seemed to him to be the most important South African guano bird. It is, however, curious that it is so rarely mentioned in the annual reports of the Superintendent of the

Government Guano Islands. Of the fuller reports that have been available only those for 1901 and 1938 comment on the bird.

Spheniscus demersus, according to an anonymous writer (Ex-Member of the Committee, 1845) who had had experience of Ichabo Island, was the most important producer of guano on the island in its original state, though the northwest corner had gannet and cormorant droppings and the southern was covered with decaying seals and their excreta. This writer concluded that about one-half the Ichabo guano was derived from penguin droppings and much of the remaining half from mummified remains of these birds. A humorous poem is quoted by the same writer, referring to the island

"Where penguins have lived since the flood or before

And raised up a hill there, a mile high or more."

He also gives a comic blazon of arms for the islands of which the supporters are "On either side a Penguin ppr. winged and beaked Or., *dexter regardant*, *sinister dormant*, *statant* on bags—empty!"

Though the contribution of the penguin was thus evidently regarded as of primary importance in the original state of the island, later, when the annual deposition was harvested on an income basis, this bird was apparently not always appreciated. Andersson (1872), though considering *Spheniscus demersus* second only to *Morus capensis* as a guano bird, writes that the "lessees of Ichaboe have considered it worthwhile to enclose the middle of the island for a distance of 300 feet by 180 feet—to prevent the Penguins from mingling their adulterated deposits with those of the gannets." The adulteration resulted from the penguins' scratching and digging below the guano deposit. The use of penguin eggs as an article of human diet has, however, led to protection and encouragement being given to *S. demersus* as well as to the less fossorial guano birds. Penguins now apparently breed on Hollam's Bird Island, Mercury Island, Ichabo Island, Possession Island, Halifax Island, Vonderling Island, Malagas Island, Jutten Island, and Dassen Island (Andersson 1872; Meise, 1938; Speight, 1940). From the last-named island, which has the most important penguin colony, up to half a million eggs

have been collected annually, as is apparent from the reports of the Superintendent of the Government Guano Islands. Roberts (1940b) indicates that he was informed by the superintendent of the islands that a few penguins are found breeding throughout the year, but that the maximum egg laying occurred in March and September, though the dates are subject to variations due to unknown causes.

The trek duiker, *Phalacrocorax capensis*, though not a close relative of *P. bougainvillei*, has developed a mode of life very similar to that of the guanay, searching on the wing for shoals of fish, in enormous flocks. Andersson says that an unbroken line may fly past for two or even three hours, and that the species breeds on almost every suitable rock or inlet from the Kunene River to Table Bay. Hentschel (1933) over half a century later refers to the lines of birds passing by the hour on their way to fish in the morning and returning to Walvis Bay in the evening. On one occasion 100,000 birds were estimated to pass.

Where all three of the important guano birds nest on the same island, the penguins are found at the top, the malagas in an intermediate position, and the cormorants in the lowest zone. W. P. Lowe (1912) says that the penguins that he observed breeding on the highest part of Ichabo in 1910 ascended to their nesting site by a regular path that passed up through the great breeding population of malagas, which apparently kept clear of the *Spheniscus* right of way. Lowe found all four species of cormorants breeding on the island, the two pairs of *P. c. lucidus* having nests in a more central region than the other three species which occupied a localized area at the periphery of the island (fig. 41).

It will be observed that not only are the geographical and climatic conditions of the Peruvian and African guano coasts comparable, but also that three comparable species of birds, filling a similar set of ecological niches, are involved in production of the deposits. Moreover, though it is not an important species, a few pairs of *Pelecanus rufescens* Gmelin breed on at least one of the African islands, namely, Seal Island in False Bay (Wyndham, 1932), so that the four most important Peruvian species all have African analogues. It is furthermore interesting that

the shifting of guano production from the burrowing and scratching penguin to the surface breeding cormorants and Sulidae took place after exploitation of the old deposits on both coasts, though southwest Africa has no guano bird to be compared to *Pelecanoides garrattii*.

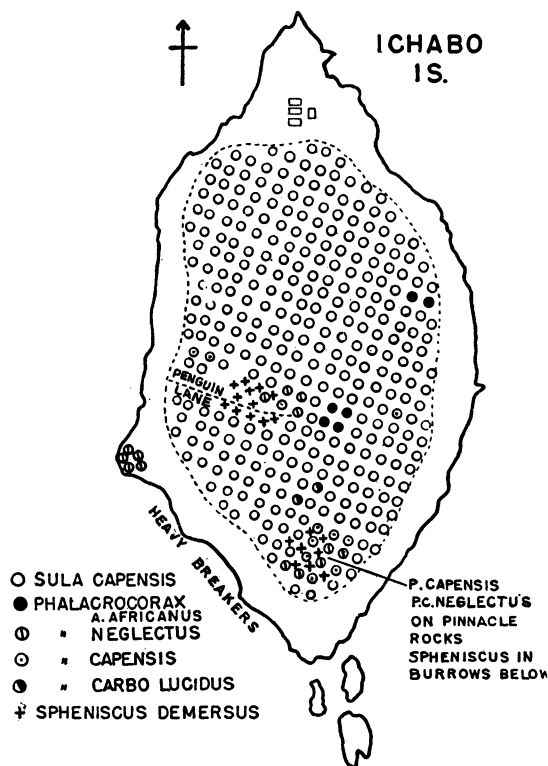


FIG. 41. Distribution of breeding birds on Ichabo Island. After Lowe.

In certain cases the colonies of particular species are clearly localized on special islets, and the full zonation is not developed. Speight indicates that while Malagas Island in Saldanha Bay has *Morus capensis* with some penguins and duikers, Vonderling has *S. demersus* and *Phalacrocorax capensis* only, without the gannets, and Jutten Island penguins, duikers, and a variety of other, less abundant, aquatic birds. Ichabo in its original condition "was literally alive with one mass of penguins," gannets and cormorants inhabiting the northwestern corner and seals the southern end of the island (Ex-Member of the Committee, 1845). Possession Island evidently was primarily a penguin

colony; Morrell says that any quantity of eggs of these birds can be obtained between August and October. The inferior guano of this island, however, consisted mainly of seal feces and the dead remains of these animals (Ex-Member of the Committee, 1845). The seal colony was exterminated, apparently by an epidemic, about five years prior to 1828 (Morrell, 1844), and a similar catastrophe was noted on islands of Angra Pequena. The Possession Island seal colony was never reconstituted (Speight, 1940). This is probably an example of the general tendency that must exist among social organisms with highly developed homing behavior that makes establishment of new colonies difficult. Such habits, coupled with occasional catastrophes, probably explain the sporadic and apparently arbitrary distributions of colonies and consequently of their excretory products. Competition for food between seals and birds is said to be sufficiently great to justify reducing the number of the former (Speight, 1940), and seal skins have formed an important part of the commercial yield of the islands. Fishermen are, moreover, apt to consider that the birds take a disproportionate amount of the yield of the sea (Gill, 1936). The chief enemy of the guano birds on their breeding islands appears to be the gull *Larus dominicanus* (Hewitt, 1938; Speight, 1940).

FLUCTUATIONS IN THE BIRD POPULATION AND IN GUANO PRODUCTION ON THE SOUTH AFRICAN ISLANDS

There is a good deal of evidence that variations in food supply, induced by variations in the meteorological conditions from year to year, cause desertion of nesting sites by the guano birds, and so reduce the production of guano and perhaps lead to declines in the bird population itself. The whole picture presented by the assembled evidence is reminiscent of the analogous phenomena on the Peruvian coast, but the variations in the African populations are evidently much less regular and probably less spectacular. It is probable that the meteorological and oceanographic factors that control the food supply of the guano birds operate in a more complex way on the African than on the South American coast. The absence of any mountain range corresponding to the great Andean

chain no doubt permits the development of less systematic and more local disturbances than occur off the Peruvian littoral.

The available evidence is derived from the annual reports of the Superintendent of the Government Guano Islands. These were published as Parliamentary Papers by the Government of Cape Colony up to 1906, by the Government of the Union of South Africa in the Journal of the Department of Agriculture from 1915 to 1925, and in the journal Farming in South Africa from 1926 onwards. The earliest report accessible has been that for 1896, which contains a little information about earlier years. The reports are of uneven value; the amount of information is moreover very variable. The Superintendents of the Government Guano Islands have, however, most kindly supplied additional material. The general variation in production is indicated in the form of a graph (fig. 42) in which the annual yield for the whole region, as well as for the two groups of islands, has been plotted against time. The information on abnormal periods follows.

1881: After two years in which the Ichabo group yielded about 5000 tons per year, the production dropped to about 1800 tons. This was attributed to a large number of birds leaving the islands in search of food (Jackson, 1897).

1892: About half the guano of the Colonial Islands was washed into the sea by three days of incessant rain in December. The loss amounted to about 1200 tons, and Jackson (1897) says that this was the only year up to the time of writing that the islands had failed to produce enough guano to satisfy the local demand.

1899: "In the annual report for last year (1898),¹ I drew attention to the fact that the prospects for the season ending 31st December, 1899, were not encouraging, although the Colonial Islands had produced a better crop than had been anticipated, and regret to add that the forecast for the coming season is not encouraging, owing to an epidemic amongst the penguins which, although more particularly confined to the Ichaboe Islands, extended in some degree even to the South East Coast, but at the time of writing

¹ The annual reports for 1897 and 1898 have not been accessible.

I may say that the mortality appears to have ceased at any rate for the present on the Ichaboe group.

"No reason can be assigned as to the cause of death, because the birds appeared to be perfectly healthy and in good condition; they simply come out of the water and drop dead as if poisoned. The young birds on the Colonial Islands also appear to have been dying of starvation" (Jackson, 1900).

1900: Yield very disappointing and prospects for the next season worse (Jackson, 1901).

1901: Any possibility of even a moderate output was destroyed by heavy rains in the early part of the year. On most of the Colonial Islands, the guano was reduced to mud or entirely washed away. Two-thirds of the yield from the Colonial Islands came from two islands inhabited by malagas. These islands produced guano because the gannets stayed very late in the season.

1902: Very satisfactory in spite of some loss due to early rains' interfering with collection on the Colonial Islands (Jackson, 1903).

1903: "The output for the season cannot be considered satisfactory, and the short fall may be accounted for by the peculiar weather prevalent during the year, which affected the migration of both fish and birds" (Jackson, 1904).

1905-1906¹: No evidence as to unfavorable natural conditions, though for 1906 the results are said to be somewhat disappointing though good. The report implies that a still better yield would have been obtained if there had not been continual poaching.

1910: Owing to continued scarcity of small fish on the coast the mortality of birds, particularly of penguins, was very great throughout this year (*in litt.*, Superintendent of the Government Guano Islands).

1914-1915²: Abnormal rains during July caused a loss of 400 to 500 tons on the Northern Islands, the climatic conditions being the most severe that had been recorded during any winter in that region. The rains affected the southern group to some extent, but the most important cause restricting production

on the Colonial Islands was a very high mortality among the penguins, "due no doubt to the prevailing scarcity of small fish on the coast." A further cause of low output was the military occupation of Seal and Penguin Islands in Luderitz Bay, and the fact that Hollam's Bird Island was not worked (Zeederberg, 1917).

1915-1916: The shortage of small fish, attributed to "very unfavorable and wet weather" at the end of 1915 continued to affect the birds seriously. They were "very tardy in taking up on the islands at the proper time," and this behavior resulted in an exceptionally late season (Zeederberg, 1917).

1916-1917: "The abnormal weather and unseasonable rains" of 1914-1916 "had the effect of throwing everything out of gear on the coast, both as regards the seasons and the incidence of a sufficient supply of fish." The breeding season was in consequence the latest that had been recorded. A prolonged period of dry weather in the first four months of 1917 enabled the birds to rear their broods and permitted collection of the guano, though the yield was reduced by unprecedented rains in April and June (Zeederberg, 1917, 1918). Owing to the decline in the number of penguins, collection of their eggs was restricted to Dassen Island in this year, certainly until 1919 and probably in all later seasons.

1917-1918: Breeding still late, but the dry summer of 1918 permitted a very good crop (Zeederberg, 1918, 1919).

1918-1919: Normal (Zeederberg, 1919).

1919-1920: Extraordinarily large crop.

1920-1921: Steady rise in production maintained, but heavy rains in January and February caused some loss.

1921-1922: Very good in spite of some losses due to untimely rains.

1922-1923: Large deposits produced, and the crop would have been greater but for torrential rains which fell before it could be collected.

1923-1924: In 1923 the penguins disappeared for some months of the year, and when they returned to the islands they seemed unable to settle down. The phenomenon is said to have been noticed once before since the occupation of the islands. There was a tendency to similar behavior on the part of the

¹ Owing to a change in the administrative year there is no proper report covering the collecting period of 1904.

² The reports appear to apply in the main to the second year of the two given.

other birds, so that the breeding season was very late. The decline in the production compared with that in the previous years is attributed to this behavior.

1924-1925: The crop to be collected in 1925 was expected to be small, apparently owing to the scarcity of young fish.

1925-1926: Abundance of small fish and favorable weather led to a somewhat prolonged breeding season and good production.

1926-1927: Very good.

1927-1928: Very satisfactory.

1928-1929: Scarcity of small fish affected production very considerably.

1929-1930: Scarcity of small fish had an unfavorable effect.

1931-1932: Very poor.

1932-1933: The duikers [*Phalacrocorax capensis*] during the last three¹ years have come to the islands in large numbers just at the beginning of the breeding season, but . . . they do not appear to want to settle down, and after building their nests and in some cases laying a few eggs, they begin to take off again, ultimately leaving the islands altogether long before the breeding season is at its height." The birds apparently remained along the coast and when they came for these short visits to their breeding stations were present in numbers. The penguins, however, appeared to have suffered an actual diminution in the size of the population. This apparently had been noted as occurring gradually up to 1931, but in the next two years the decline became much more conspicuous, so that an absolute prohibition of taking eggs seemed necessary in 1932, though in previous times up to half a million eggs were taken annually without putting an undue strain on the population. The cause of the decline was in part attributed to the use of penguins as bait for "crayfish," *Jasus lalandii* (Milne Edwards), but undoubtedly this was merely an aggravant, because the diminution took place in areas where no fisheries existed. There was said to have been a fair quantity of small fish available, but it had been observed that reductions in the penguin population generally coincided with a decline in the snoek, *Thyrssites atun* (Euphrasen) fishery. During the 1932-1933 season the

¹ The original reads "there," but the above emendation is presumably correct.

decline in this fishery had proceeded so far that the species was not present in the commercial catch.

1933-1934: The poorest period hitherto noted, partly owing to the continued abnormal behavior of the birds and partly owing to the heavy rains just prior to the period of guano collecting on the Northern Islands.

1934-1935: Some improvement but the same adverse factors operating as in the previous season, the rains at Lambert Bay and at Bird Island destroying some 500 tons of guano. Restriction on the export of crayfish had reduced the fishery around the islands, and the penguin population was increasing.

1935-1936: No report available.

1936-1937²: During the season "bird life has suffered owing to a scarcity of food, and climatic conditions have also seriously affected the breeding and nesting . . . In some cases, the disturbance by gulls has caused large flocks of duikers to leave their nests and their young" (Hewitt, 1937).

1937-1938: Conditions very similar to those of previous year, the birds taking up on the islands late and in small numbers and some leaving before nesting began. The malagas were said in general to be much less easily disturbed than the other birds. The season was apparently climatically abnormal, long-continued southwest gales at the beginning of the breeding period causing the birds to desert most of the islands. Penguin eggs were again taken in 1938, but the breeding season terminated abnormally soon and the birds moulted early. The yield was very low compared to that of earlier decades. An increase in the number of gulls seems to have been observed, partly owing to the dispersion of a colony that was associated with a whaling station at Langebaan; the gulls started visiting the islands when the station was closed. The output for the 1937-1938 season was said to be the lowest that had been recorded. This last remark clearly applies only to the years subsequent to the formation of the Union of South Africa.

1939: Many chicks died of an unknown disease on Malagas Island, but the total number of gannets was little reduced.

When such data as are available are con-

² All the collecting was done after the middle of January; this is said to be later than in other years.

sidered, it is clear that the climatic and biological factors influencing guano production operate in a less regular and more complex way on the South African than on the Peruvian coast. On the Peruvian islands, the incidence of northerly winds, a warm counter current, rain, unavailability of food fishes, and other phenomena of the abnormal years present a complex but intelligible pattern. On

similar to that left by the more extensive documents on like events on the Peruvian coast. Gilchrist (1914a), though he gave no dates for his observations, concluded that the abnormal behavior of *Phalacrocorax capensis* was due to starvation rather than disease. He also (1914b) calls attention to the fact that the available statistics for the catch of *Thyr-sites atun* and for export of salt fish, mainly

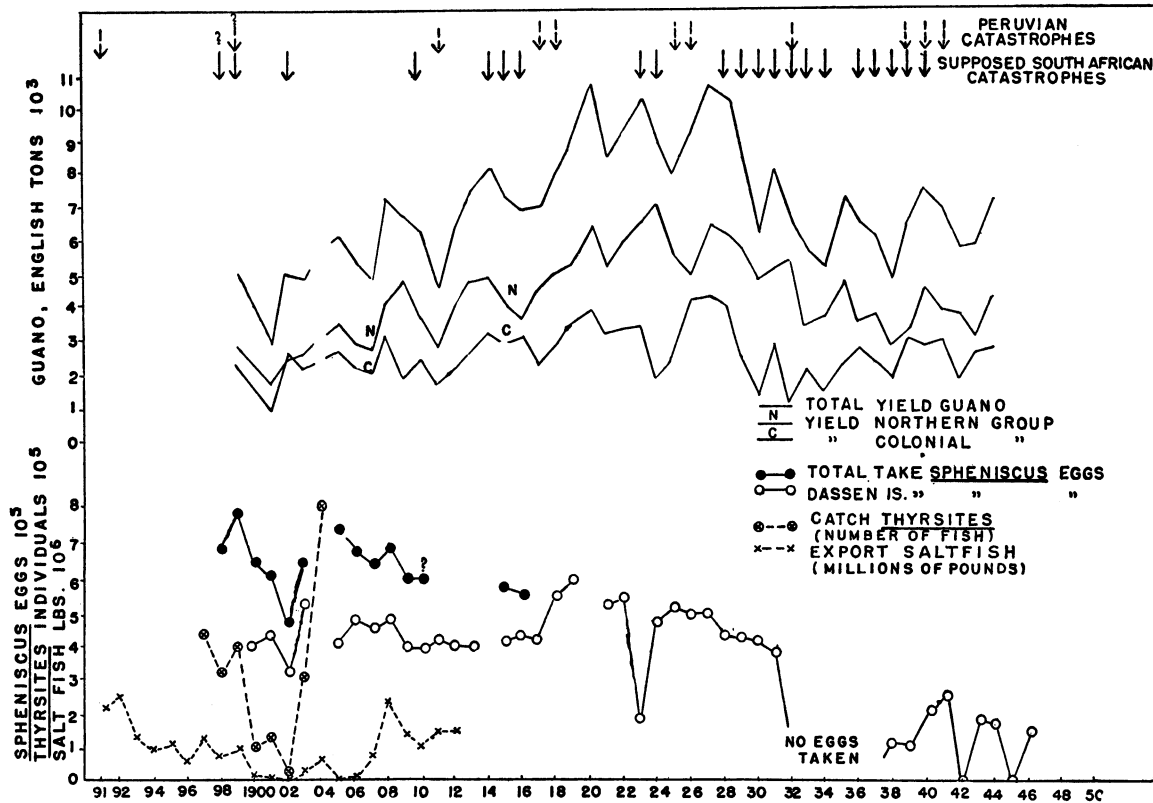


FIG. 42. Total yield of guano from Government Guano Islands, and from Northern and Colonial groups separately, of penguin eggs from Dassen Island, and from all islands exploited, of the landings of *Thyr-sites atun* and of salt fish exported; and of probable dates of catastrophic declines in the bird populations on both the South African and Peruvian coasts.

the South African coast the existence of such integrated phenomena, though probable, has never been demonstrated, while southwest gales early in the breeding season and winter rain storms prior to the completion of the collection of guano, meteorological events without parallel on the Peruvian coast, may injure the breeding birds or wash their products into the sea. When allowance is made for such purely South African events, the accounts of failure of food supply and of desertion of nesting sites give an impression very

of this species, show a minimum in 1902, when mortality of penguins in the Colonial group began to be observed. *Thyr-sites* appears to feed largely but not exclusively on *Sardina sagax*, and its abundance may be a measure of the abundance of the latter off the Colonial Islands. Penguin egg production dropped off markedly at the time of the minimum and rose as the *Thyr-sites* catch rose. Later evidence of falling penguin populations about 1915 accompanied by a fall in guano production is also available, and the same situation

appears to have occurred in 1923–1924 and about 1929–1933, after which time the taking of penguin eggs was prohibited. During this latter decline, *Thyrssites*, as has been indicated, dropped out of the commercial catch. Too much reliance should not be placed on the penguin egg data as a measure of the population of guano birds, for they relate solely to the southern islands on the west coast, and a catastrophic decline in production of eggs, as in 1923, can occur in a year in which the guano crop is not greatly reduced.

It seems reasonably certain that the depression years in Peru are not, in general, depression years on the South African coast, but if we consider only the data relating to depression caused by a decline of food supply or accompanied by abnormal behavior of birds, so excluding fluctuations due to the washing away of guano, there seems to be a tendency for the depressions on the South African coast to anticipate those of the Peruvian coast.

SOUTH AFRICA	PERU
1881	?
?1898–1899	?1899
1903	?
1910	1911
1914–1916	1918
1923–1924	1925–1926
1929–1933	1932
1936–1939	1939

The greater irregularity of the South African curve, which does not depend entirely on the catastrophes occasioned by food supply, makes any detailed comparison with the Peruvian curve unprofitable. The tabulation of the years of apparent depression in food supply on the two coasts perhaps implies some long-period oceanographic change propagated through the Antarctic Ocean. If further observations confirm this very tentative suggestion it is obvious that the phenomena will acquire extraordinary oceanographic significance.

DESCRIPTION OF THE NORTHERN ISLANDS

The following islands off the coast of southwest Africa constitute the Northern group. As far as is known, the old guano, at least on the more productive of the islands, was a moderately good nitrogenous material.

HOLLAM'S BIRD ISLAND

LATITUDE 24° 39' S., LONGITUDE 14° 32' E.

Described as a rock 12.2 meters high and apparently not over 400 meters in diameter. It is evidently one of the more inaccessible islands of the coast. The near-by Albatross Rock in latitude 24° 45' S. yielded, according to Schultze, less than 1 ton of guano per year.

MERCURY ISLAND

LATITUDE 25° 40' S., LONGITUDE 14° 50' E.

In the entrance of Spencer Bay, described as a bare, rugged rock about 730 meters long, 275 meters wide, and 38 meters high. It is said to appear as a white pyramid.

ICHABO ISLAND

LATITUDE 26° 17' S., LONGITUDE 14° 56' E.

In Douglas Bay, lies about 1.2 kilometers from the mainland, and is about 800 meters long and 230 meters wide. It is said to have a maximum altitude of 9.1 meters and, as far as can be judged from old illustrations (pl. 13, fig. 3), has a flat interior plain. Ichabo had by far the largest cap of old guano of all the Northern Islands and continues to produce much more modern guano than the other members of the group.

SHARK, PENGUIN, AND SEAL ISLANDS

LATITUDE 26° 38' S., LONGITUDE 15° 06' E.

These, with Halifax Island just to the southwest, are guano islands within Angra Pequena or Luderitz Bay. They are all rather high, Halifax Island reaching 37.2 meters, Shark and Seal Islands 42.1 meters, and Penguin Island 48.1 meters. Just to the south of Angra Pequena Bay, North and South Long Islands are also guano islands. North Long Island is described as low and level.

POSSESSION ISLAND

LATITUDE 26° 58' S., LONGITUDE 15° 13' E.

In Elizabeth Bay, a very narrow island about 3 kilometers long with a maximum altitude of 20.4 meters. Its coasts are rocky and nearly perpendicular. Some adjacent rocks, as well as the main island, apparently yield guano.

POMONA ISLAND

LATITUDE 27° 10' S., LONGITUDE 15° 17' E.

Described as 15.5 meters high, lying close off shore and appearing from the sea as two low hummocks.

PLUMPUDDING, SINCLAIR, AND
ROAST BEEF ISLANDS

BETWEEN ABOUT LATITUDES 27° 50'
AND 28° 00' S.

These, and perhaps some adjacent rocks, yield guano and are apparently the most southern members of the Northern group, though Range (1912) indicates a South Island, south of Sinclair Island, as producing guano. No details are available about any of these islands.

An anonymous author (Anon., 1845b) mentions Boyds, Bob, and Merman Islands as exhausted in 1845 and Ludovic Island as still containing guano in that year. These are probably synonyms of some of those listed above.

The first observation of guano on the Northern Islands was made by Morrell (1852), an American sealer who had visited Ichabo in 1828 and had killed a very large number of seals there. Morrell reported 25 feet of bird droppings on the northern side of the island. This information, recorded in his book on his voyages, suggested to a Mr. Andrew Livingston of Liverpool that a workable deposit existed. The early history of exploitation is confused and dishonest but irrelevant to the present work. The first cargoes seem to have been shipped in March and April, 1843. By the end of February, 1845, all the good guano had been removed. Voelcker (1877) states that the good old guano was all taken in 1843, but that a poor grade of material

was still sold in 1849. Nesbit (1860) indicates that poor-grade guano was still imported in 1858, though this may have come from other localities. The other Northern Islands were exhausted as quickly as was Ichabo. Mercury Island was cleared by September, 1844 (Anon., 1845a), and Plumpudding, Boyds, Bob, Possession, Merman, Penguin, and Seal Islands, some of which cannot now be identified, were exhausted about the same time (Anon., 1845b). Late in 1845, only an unidentified island called Ludovic between Possession and Angra Pequena, and Hollam's Bird Island retained their covering. The quantities present initially on these islands were estimated (Ex-Member of the Committee, 1845; Anon., 1845a, 1845b) as:

	Tons
Plumpudding Island	2,500, removed
Possession Island	4,000-5,000, initially
Small island southwest of Pedestal Point	8,000
Penguin and Seal Islands	3,000, removed
Ichabo Island	200,000, initially

It will be observed that the original deposit on Ichabo vastly exceeded that of the other islands but was small in comparison with that present on some of the Peruvian islands. It is probable that Ichabo has a more favorable form for accumulation than do most of the other African islands, being relatively flat and yet sufficiently elevated to prevent the material from being washed away during high seas.

The following statistics of guano collected, in English tons (1 English ton = 1.016 metric tons) per annum, to the nearest ton, indicate that in recent times also Ichabo has been the most productive of the Northern Islands (Schultze, 1907; Jackson, 1900-1907; Zeederberg, 1916):

ISLANDS	1898	1899	1900	1901	1902	1903	1905	1906	1914	1915	1916	1197
Hollam's Bird	50	30	60	50	50	55	55	94	386	—	—	—
Mercury	120	—	130	100	120	130	140	175	216	200	203	220
Ichabo	1300	1235	980	950	1300	1500	2500	1800	2603	2555	2245	2168
Penguin and Seal	15	133	38	15	15	10	15	—	120	—	—	549
Halifax	160	210	260	120	160	140	80	80	244	240	225	370
Possession	900	450	670	400	600	600	500	600	933	821	830	1023
Pomona	80	40	80	40	80	50	60	60	100	100	100	109
Sinclair	—	—	—	—	—	—	85	75	130	130	100	100
Plumpudding	—	—	—	—	—	—	55	—	100	95	50	50
Sinclair and Plum- pudding	120	113	110	70	120	120	—	—	—	—	—	—

All the islands save Ichabo are clearly very unproductive compared with Peruvian islands of comparable size.

No really detailed account of the original deposits on any of the Northern Islands exists. The best description is that given by an "Ex-Member of the Committee" (1845) appointed to regulate loading and to control the very frequent disputes at Ichabo. The guano deposit was thickest and of the best quality on the northern side of the island, where the "Ex-Member of the Committee" states the thickness was 40 feet. This concentration on the lee side has been attributed to a preference by the guano birds for the more sheltered part of the island as a site for nesting (Andersson, 1861), in opposition to what Vogt observed in Peru. This may be a specific difference in requirements of the birds, or it may be owing to lower air temperatures at the higher latitude of Ichabo. It is, however, quite possibly an erroneous observation, and the unequal depths may be due to aerodynamic factors. Watson (1930) quotes an unpublished journal of Washington Fosdick (on board the schooner "Emmeline," 1843-1844) who estimated the maximum thickness as 50 to 60 feet. The same observer states that the guano was so consolidated that the diggers had "not only to use the pick-axe but the beetle and wedge" also. The thin seal guano on the southern side of the island was evidently inferior. The remarks made in the contemporary accounts as to the presence of the decaying bodies of seals were probably occasioned by the remains of Morrell's ruthless seal hunt and are not necessarily typical of the natural state of the island. After the island was cleared new guano was deposited. This seems to have been worked first about 1860, for Anderson (1861) received Ichabo samples containing 11.49% to 12.85% N in 1859 to 1861. Voelcker (1877), on the authority of Daniel de Pass, a proprietor of Ichabo, says that 23 years after the old material was removed a good breeding colony of birds had been established. In the late seventies the schooner "Delia Chase" set out from New Bedford to Hollam's Bird Island and found the new deposit to be several feet thick in places; none was loaded as the British authorities were reserving the right to collect the material (Watson, 1930).

A little unsatisfactory evidence as to chronology can be derived from two burials discovered during the course of the original exploitation. In one case (Anon., 1866) the mummified body of a man was said to have been found after 1840 under 40 meters of guano on an unspecified island, presumably Ichabo. The mummy was associated with a piece of wood, allegedly inscribed "Christoph Delano 1421." Both the depth and date are clearly impossible. Meise reads 40 feet for 40 meters, which emendation is almost certainly correct, and 1721 for 1421, which is plausible, the continental 7 being easily misread for 4. The mummy was said to have been placed on public exhibition at Havre de Grace; inquiry of the Chamber of Commerce of that city, who most kindly put a letter in a local newspaper, has failed to elicit further information. If Meise's emendation of the original account of the find be accepted, a rate of deposition of about 10 cm. per year is indicated if the body had been left on the surface, or 8.7 cm. per year if it had been buried at a depth of 2 meters. This estimate is in general agreement with the most probable rate of deposition on the Peruvian islands in modern and in pre-Colonial times. The circumstances attending the discovery are, however, so obscure that little value can be given to such an estimate. It must also be remembered that the body may have been inserted into a lateral excavation at the bottom of a cliff-like guano face.

The second case of the discovery of a burial, in 1844, is reported by Watson (1930), without citation of his source. This body was also provided with an inscription reading 1689, and was reported as lying under 18 feet of guano. Adopting the same convention as in the previous paragraphs, the rate of deposition is between 2.3 and 3.6 cm. per year. This lower estimate is in general agreement with the most probable rate of deposition on the Peruvian islands in Colonial times. Even a rate of deposit as little as 2.3 to 3.6 cm. per year is in accord with the observation that several feet had accumulated on Hollam's Bird Island, 20 to 35 years after that locality had been exhausted in the feverish guano rush of the 1840's.

It is interesting to note that Haughton (1933) states that the administrator of the

Government Guano Islands informed him that in his opinion loss of guano by deflation was not great on the African islands, owing to the hardness of the relatively fresh material. This, of course, may well have been less

	I	II	III	IV	V	VI	VII
Moisture	17.54%	16.33%	17.59%	17.97%	19.30%	22.52%	24.22%
Organic matter and NH_4 salts	46.98	51.47	53.74	45.68	45.20	44.73	46.08
Total N	12.29	13.16	14.12	12.18	11.95	11.89	12.43
CaO	6.49	6.51	6.36	6.70	9.89	8.26	9.72
P_2O_5	8.48	7.33	7.45	8.28	10.46	9.15	11.10
MgO, alkalis, etc.	8.76	7.79	9.91	6.62	8.75	5.99	7.68
Insol.	14.74	10.67	7.03	14.75	6.40	9.35	1.20

true in the past owing to the scratching and digging of penguins.

Low, raised strand lines have been observed around Plumpudding and Sinclair Islands (Du Toit, 1917), and though there are no observations relating to the other Northern Islands it seems certain that their surfaces have been exposed for at least a good fraction of post-Pleistocene time. Yet whatever the value, and it may be little enough, that can be set on the details of the two burials recorded above, if any bodies were actually discovered at depths considerably in excess of the meter or two likely for the depth of a grave, it is certain that accumulation can have taken place during but a few centuries. The arguments advanced when discussing the Peruvian localities, that the oldest deposit was of relatively recent origin, appear to apply to Ichabo also.

CHEMISTRY OF GUANO FROM THE ISLANDS OF THE NORTHERN GROUP

Most of the published analyses of modern guano from the west coast of southern Africa are derived from mixed material from both the Colonial and Northern groups. Analyses of this kind have been published in the annual reports. For 15 years in the periods 1916–1919 and 1925–1938 the mean and extreme data are as follows:

	MEANS	EXTREMES
Total N	10.67%	10.2–11.2%
Total P_2O_5	11.01	9.8–12.7
2% citric acid-sol. P_2O_5	10.39	9.3–11.5
Water-soluble P_2O_5	3.16	2.8– 3.53
K_2O	1.89	1.1– 2.5
CaO (6 anal.)	11.17	10.5–12.0

Analyses of modern guano, collected in

1899 and specifically designated as from Ichabo (I–V), have been published (Jackson, 1900), and Schultze, who quotes two of these analyses, gives two more (VI, VII) referring to the same year, from unspecified Northern Islands:

It will be observed that these analyses approach more closely those of modern Peruvian guano than do the analyses for the mean annual crop of Northern and Colonial Islands taken together. This suggests that on some of the Colonial Islands enough decomposition occurs prior to collection to produce guano appreciably poorer in nitrogen than is the mean, to compensate for the amount of nitrogen in excess of the mean apparently present in the Ichabo samples.

The only adequate analysis of old material was made on commercial Ichabo guano by Waldie in 1844, and published as the appendix to a reprint of Morrell's voyages (1852). The analysis has been recomputed as constituents:

H_2O	23.35%
Indet. organic	11.00
Waxy material	1.6
Oxalic acid	23.31 [= 18.65 as $(\text{CO}_2)\text{O}$]
CaO	6.76
MgO	0.69
Na_2O	1.68
K_2O	1.63
$(\text{NH}_4)_2\text{O}$	17.04* (= 9.53% N · NH_3)
Cl	2.24
SO_3	5.25
P_2O_5	9.25*
Insol.	0.2

* Computed on the assumption made throughout the present work, that the "phosphate of ammonia" is $(\text{NH}_4)_2\text{HPO}_4$. If in the original analysis this substance is calculated as triphosphate the $(\text{NH}_4)_2\text{O}$ becomes 18.08%, equivalent to 10.09% N · NH_3 , the P_2O_5 becomes 8.75%. It is assumed that the value for water in the analysis represents a direct determination not involving essential water in ammonium salts.

The most remarkable feature of this analysis is the very high oxalate content and the

absence of uric acid. The oxalic acid of the analysis corresponds to 43.5 parts of uric acid, which on decomposition would produce 25.9% $(\text{NH}_4)_2\text{O}$. It is clear that some ammonia has been lost. If, in the place of all the oxalate and ammonia, the uric acid be substituted, the original guano would have contained 40.6% uric acid, which is very reasonable. In the original analysis the oxalate is assigned as 18.34% ammonium and 14.23% calcium oxalates. Some such distribution is very probable, though the exact partition between the bases obviously involves an arbitrary element. The general character of old Ichabo guano as revealed by this analysis is confirmed by Teschemacher's (1845) statement that such guano contained no uric acid and by an anonymous analysis (Anon., 1847) which gives 11.1% N, 25% "phosphates," and 20% "oxalic etc." acid. It is evident that the Ichabo guano had suffered slightly greater diagenetic change than that from the Chincha Islands or Guañape. This is in harmony with the slightly greater precipitation on the southwest African coast; at Ichabo "dews and fog are very heavy, with sometimes heavy rain for about four hours" (Anon., 1845a), though the last event must be very rare. The molecular ratio of calcium to phosphate is 1:0.56.

Two less informative analyses based on old southwest African material from known

	I	II
H ₂ O	25.98%	18.89%
Organic matter	41.52	—
Sand	0.44	—
$(\text{Al,Fe})_2\text{O}_3$	0.48	—
P ₂ O ₅	11.74	13.40
CaO	9.95	12.42
MgO	0.84	—
K ₂ O	4.20	—
Na ₂ O	0.34	—
NaCl	1.61	—
SO ₃	1.06	—
N	7.92	8.88

Omitting gypsum, the molecular ratio $\text{CaO}:\text{P}_2\text{O}_5$ for the Ichabo material is 1:0.466, essentially as in some unleached Peruvian guanos. The phosphate in excess of $\text{Ca}_3\text{P}_2\text{O}_8$ is referred by Nesbit to potassium phosphate, presumably an analytical convention.

Waldie (1845) gives four proximate analyses of Ichabo guano, indicating:

	MEANS	EXTREMES
Moisture	25.60%	23.3–27.4%
Organic matter and NH ₄ salts	40.43	34.9–50.6
$(\text{Ca,Mg})_3\text{P}_2\text{O}_8$	23.25	18.3–28.6
= P ₂ O ₅ (assuming negligible MgO)	10.69	8.4–13.1
Alkalis, etc.	6.45	4.7– 8.8
Sand	0.35	0.2– 0.4
Total N	9.38	6.6–12.2

Nesbit gives the following analyses based on material said to have been from Ichabo, imported between 1853 and 1858 inclusive:

	1853	1856	1857	1857	1858	1858
Moisture	17.20%	14.10%	12.29%	23.12%	13.50%	17.08%
Organic matter, etc.	20.45	25.91	14.45	28.45	17.50	17.49
CaO	—	5.34	13.16	11.10	19.38	13.82
MgO	—	—	—	—	—	2.43
Alkaline salts	5.80	3.82	2.96	7.67	12.55	3.75
$(\text{Al,Fe})_2\text{O}_3$	—	—	1.35	1.33	5.53	tr.
P ₂ O ₅	9.31	5.28	9.49	8.79	10.07	9.38
CO ₂	—	—	1.00	—	5.87	—
SO ₃	—	—	0.98	1.02	—	2.40
Silica	36.25	45.60	44.32	18.50	15.60	33.65
N	4.93	5.99	1.90	5.50	2.89	3.07

localities also exist. The first relates to guano from Ichabo (I) imported immediately after the discovery of the deposit (Nesbit, 1860), the second to guano from Damaraland (II) presumably Cape Cross Bay (A. Grimm in Ullmann, 1906).

The immense quantity of siliceous matter in these guanos was apparently also characteristic of the guanos of the poorer islands even in their original condition, for in the appendix of the reprint of Morrell's voyages in which Waldie's main analysis is given, it is stated that the available matter (apparently

everything except sand, water, and possibly calcium carbonate and sulphate) of the African guanos was:

Ichabo Island	77%
Angra Pequena Islands	69
Possession Island	61

The Possession Island guano, imported prior to April, 1843, must have contained a large amount of siliceous or other extraneous matter.

Waldie also gives an analysis of an African guano stated to be from Round Island, a locality that has not been identified:

Water	25.1%
Sand and stones	20.0
Organic matter and NH_4 salts	17.5
$(\text{Ca}, \text{Mg})_3\text{P}_2\text{O}_8$	29.0
$= \text{P}_2\text{O}_5$ (assuming negligible MgO)	13.3
Alkaline salts	7.0
Total N	2.6

Mineralogically the Ichabo deposit was evidently comparable to that of Guañape, as might be expected. The occurrence of a mixed potassium ammonium sulphate, of ammonium phosphate and of stercorite, as discrete crystalline minerals in both deposits, has already been noted.

DESCRIPTION OF THE COLONIAL ISLANDS

There is little descriptive matter relating to the Colonial group, which includes the following islands.

ELEPHANT ROCK

LATITUDE $31^\circ 39'$ S., LONGITUDE $18^\circ 09'$ E.

Off the mouth of the Olifants River, 15.2 meters in altitude.

PENGUIN ISLAND

LATITUDE $32^\circ 05'$ S., LONGITUDE $18^\circ 10'$ E.

Often called Lambert Bay Island, in the bay of that name, 12.2 meters in altitude. Small mainland deposits have been recorded in Donkin's Bay between this locality and the last (Ex-Member of the Committee, 1845).

PATERNOSTER OR SEAL ISLAND, AND JACOB REEF

LATITUDE $32^\circ 57'$ S., LONGITUDE $17^\circ 52'$ E.

The former is off Great Paternoster Point. The latter, 3.7 meters in altitude, was said by

Speight to have seals only, though officially a guano island.

JUTTEN, MARCUS, MALAGAS, MEUW, SCHAPEN, AND VONDERLING ISLANDS

The first named is at latitude $33^\circ 05'$ S., longitude $17^\circ 57'$ E. and is 36.3 meters in altitude. The first five islands named are at the entrance of, or within, Saldanha Bay, and Vonderling is just to the south. Malagas and Marcus Islands are said to be planed at the 20-foot level, while Jutten Island is fringed by an old raised beach (Du Toit, 1917). It is probable that Isle Julien and Isle Marens (Anon., 1845b) are manuscript misreadings of Jutten and Marcus Islands, respectively. Malagas Island is the most important of all the Colonial Islands, having a great colony of *Morus capensis*.

DASSEN ISLAND

LATITUDE $33^\circ 26'$ S., LONGITUDE $18^\circ 06'$ E.

Between Saldanha Bay and Table Bay, 19.2 meters altitude, described as a rock covered with sand. It has been the site of the most important penguin colony during the present century and is the main source of penguin eggs.

DUIKER KLIP

LATITUDE $33^\circ 45'$ S., LONGITUDE $34^\circ 10'$ E.

In Hout Bay.

SEAL ISLAND

LATITUDE $34^\circ 15'$ S., LONGITUDE $18^\circ 40'$ E.

In False Bay.

DYER'S ISLAND

LATITUDE $34^\circ 40'$ S., LONGITUDE $19^\circ 20'$ E.

A low rocky islet off the Bredasdorp coast.

BIRD ISLAND

LATITUDE $33^\circ 50'$ S., LONGITUDE $26^\circ 17'$ E.

In Algoa Bay, with the associated Seal and Stag Islands.

These islands are low and rocky, Bird Island, which is the largest, being about 730 meters long and 10 meters high. Seal, Dyer's and Bird Islands lie in the region of the warm Agulhas Current and therefore in a quite different hydrographic province from that of the other guano islands.

TABLE 12
ENGLISH TONS (1 = 1.016 METRIC TONS), TO THE NEAREST TON

	1898	1899	1900	1901	1902	1903	1905	1906	1914	1915	1916	1917	1918	1919
Elephant Rock	41	73	41	30	25	17	28	9	23	33	35	30	20	21
Penguin I., Lambert Bay	468	753	288	32	321	222	202	377	372	203	309	275	221	282
Paternoster I.	61	123	82	26	70	63	55	44	81	21	65	91	44	73
Malagas I.	776	875	608	485	689	889	1100	696	1118	1053	1023	1024	1058	1150
Jutten I.	108	165	144	51	378	391	302	237	521	448	407	255	430	775
Marcus I.	78	121	57	17	88	85	146	72	133	95	85	—	—	—
Vonderling I.	60	87	55	3	93	—	174	73	28	96	29	18	—	—
Dassen I.	342	267	34	—	240	227	267	271	351	214	359	125	257	771
Duiker Klip	7	22	—	—	2	—	—	—	—	—	—	—	—	—
Seal I.	65	13	—	19	—	—	—	—	—	17	20	29	28	—
Quoin Point	—	—	6	—	—	—	—	—	—	—	—	—	—	—
Dyer's I.	240	241	155	167	254	232	131	433	458	576	611	331	665	230
Bird I.	200	60	171	200	197	150	260	90	216	234	206	ca.200	218	280

Little is recorded as to individual occurrences. According to the Ex-Member of the Committee, Malagas Island bore 60,000 tons of guano, evidently greatly exceeding the other islands in productivity; the Paternosters in St. Helena Bay, about 3000 tons, and Elephant Rock, the most northern of the Colonial Islands, about 1500 tons. Another account (Anon., 1845b) estimates the amount on Malagas Island as 48,000 tons and states that on Isle Julien in Saldanha Bay the guano is not of good quality and on Isle Marens it is mingled with feathers and broken shells. The same authority indicates about 10,000 tons on Seal Island in False Bay. The yields for certain years of the present century indicate the continued importance of Malagas Island. Penguin Island in Lambert Bay, Dyer's Island, and Bird Island appear also to be significant, though specific notice of old deposits does not exist for the first two of these localities, and the old Bird Island material was very inferior.

CHEMISTRY OF GUANO OF THE COLONIAL ISLANDS

One analysis (Flack, 1916) refers specifically to a sample of mixed guano from Malagas, Marcus, and Jutten Islands:

Total N	10.94%
Total P ₂ O ₅	13.80
Citrate-soluble P ₂ O ₅	13.47
Water-soluble P ₂ O ₅	4.11
CaO	12.49

It will be observed that this analysis refers to a material little different from the mean guano from all south and southwest African sources. If the guano from some of the Northern Islands is actually a little richer in nitrogen than the mean, as seems likely, that from some of the southern islands is somewhat poorer in nitrogen than the mean.

The old guano on the Colonial Islands was evidently much leached, as is to be expected from the rainfall data. Since the Malagas Island deposit was the most extensive, analyses of the old Saldanha Bay guano of commerce probably mainly refer to that locality. Three samples from unspecified localities analyzed by Nesbit contained 0.18% to 1.34% N. Nesbit gives four proximate analyses of material received in 1852-1854 from Saldanha Bay:

Ca ₃ P ₂ O ₈	57.25-63.50%
Organic matter	11.91-19.05
N	tr. - 1.85

A later sample received in 1858 was almost half silica (48.80%), but contained 1.69% N. This sample apparently had some of the phosphate in combination with iron and alumina, the analysis giving 6.17% (Al,Fe)PO₄. Ullmann gives an undated analysis by Gilbert:

H ₂ O	17.04%
CaO	24.26
MgO	0.97
(Al,Fe) ₂ O ₃	2.27
P ₂ O ₅	24.51
N	1.41

The Algoa Bay deposit on Bird Island is the only other known locality for which analyses exist. The material was very inferior, consisting mainly of gypsum, and working was soon abandoned (Anon., 1845b), though the modern colony of *Morus capensis* now produces guano of value. Two partial analyses of the old material exist:

	NESBIT (1860)	GROUVEN (in ULLMANN, 1906)
H ₂ O	14.00%	20.25%
Organic (ign. loss)	3.22	12.10
CaSO ₄ ·2H ₂ O	71.13	—
P ₂ O ₅	4.64	6.68
SiO ₂	1.55	—
N	0.42	0.43

One of the most interesting aspects of the Saldanha Bay guano was the occurrence in it of the mineral struvite, (NH₄)MgPO₄·6H₂O (=guanite of Teschemacher, 1846). This mineral seems to form easily when ammonia and phosphate are liberated in diluted sea water, as in the process of canning shrimp and lobster (Purcell and Hickey, 1922; Palache, 1923). The resulting crystals are often mistaken for broken glass by agitated housewives. Struvite is also known in bat caves and in places where considerable decomposition of bones and cattle dung have enriched percolating water. There is also a curious case of the finding of the mineral in the lung of a human cadaver in the dissecting room at Oxford, but it is not clear if the occurrence was due to natural postmortem changes, or the action of preservatives, or some abnormal condition during life (Porter, 1924). Karmrod's analysis implies the existence of magnesium ammonium phosphate dispersed throughout the Chinchá guano, but there is no direct evidence of its occurrence. One of two samples of "concrete guano" forming massive lumps, and one of a very saline guano (19.222% hydrochloric acid) analyzed by Denham Smith may have contained struvite; the main inorganic constituent of the fraction soluble in hot, but insoluble in cold, water seems to be ammonium and magnesium phosphates, though the solubilities are not in accord with that of struvite which is slightly less soluble in hot than cold water. Struvite also occurred in the phosphatic guano of Baker Island.

ANCIENT DEPOSITS AROUND SALDANHA BAY

In addition to these deposits, there is abundant evidence (Du Toit, 1917) of the former existence in the Saldanha Bay region of extensive bird colonies on former islands, now an integral part of the mainland (fig. 43). The guano of these colonies phosphatized not merely a shelly limestone, but even more extensively the plutonic rocks of which the islands were formed.

The phosphatized shell breccia occurs on the southern side of Hoedjes Point, a peninsula running east from the mainland forming the northern coast of the entrance of Saldanha Bay. The deposit clearly represents the result of the phosphatization of a shelly beach deposit. The base of the shell deposit lies 3.7 meters (12 feet) above sea level, the top of the deposit at its thickest 5.7 meters (19 feet) above sea level. It occupies a depression cut in the granite of the peninsula; a similar small bay not far off is accumulating a shell deposit today. The phosphate thins out at the sides of the exposure, but on the north side of the peninsula there is another exposure of phosphate, so the deposit may be more or less continuous around Hoedjes Point. The main exposure, on the south side of the point, is covered with a recent limestone, the *Dorcasia* limestone, containing living species of terrestrial mollusks. Only the lower part of the shell deposits appears to be phosphatized, so that the thickness of the phosphate is about 1.1 meters (3.5 feet). The upper boundary of the phosphatized part of the shell breccia is quite sharp. The lower part is a hard, resinous, streaky phosphorite containing cavities; in the upper part there are remains of shells, which have been dissolved to form the cavities of the lower part. Du Toit thinks that, at the time of phosphatization, Hoedjes Point formed a small bird island from which guano slipped, or guano solution percolated, onto the shelly deposits forming on the beach. Chemically, the material of the phosphate deposit contained from 34.41% to 35.9% P₂O₅, with an excess of CaO; one sample gave 34.47% P₂O₅ and 47.13% CaO. A small amount of carbonate was demonstrated qualitatively.

The large aluminum phosphate deposits of Saldanha Bay lie at a higher level than the

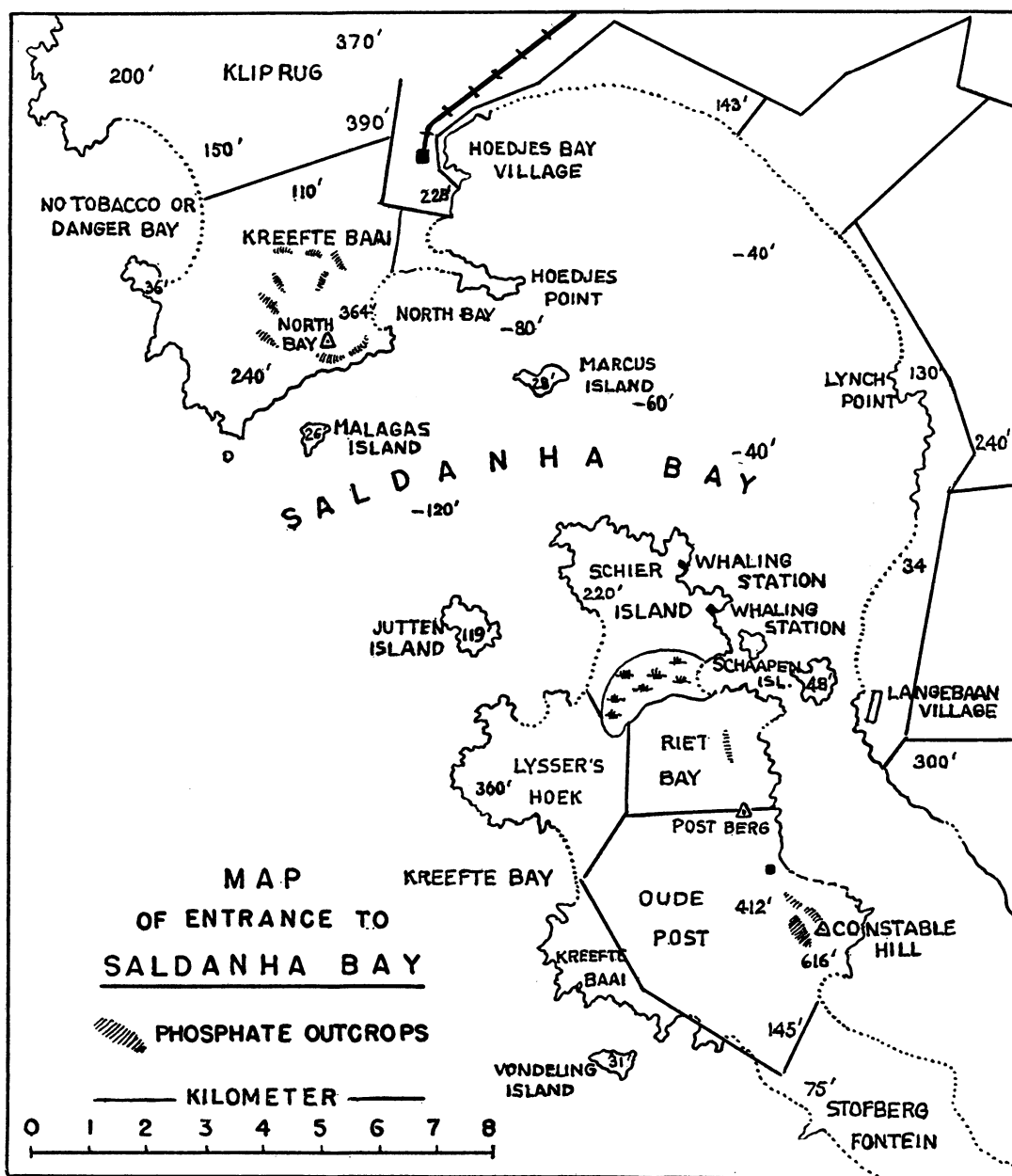


FIG. 43. Map of Saldanha Bay to show position of modern islands and ancient phosphatization. After Du Toit. Reproduced under Government Printer, Copyright Authority No. 833, of November 23, 1949.

phosphorite just described. Their lower limit is at about 15 meters (50 feet); their upper limit at about 110 meters, or possibly 150 meters. The deposits are distributed around certain hills of granite and quartz-porphry and represent the result of the interaction of guano solutions with such rock or its decom-

position products. The hills on which the material is found clearly bear a marine terrace, the inner edge of which, at about 15 meters, corresponds to the base of the phosphate. When the sea surface lay at this altitude, the hills would be islands, evidently with large bird colonies. The most important

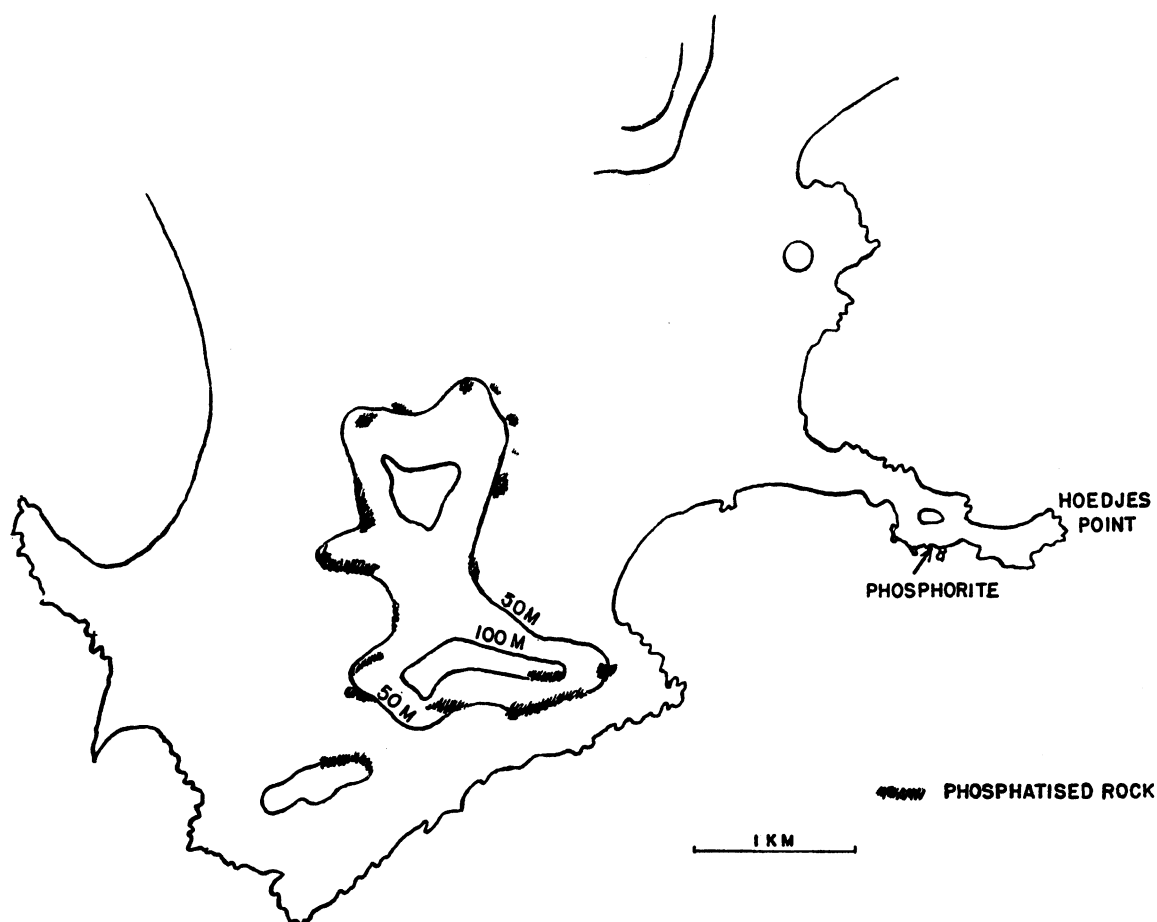


FIG. 44. Map of occurrence of phosphatization on the northern side of the entrance of Saldanha Bay. Modified after Du Toit. Reproduced under Government Printer, Copyright Authority No. 833, of November 23, 1949.

of the occurrences are on the farm Kreefte Baai (fig. 44), north of the entrance of Saldanha Bay, and on Constable Hill on the farm Oude Post, south of the entrance. The northern deposit was believed to contain hundreds of thousands of tons, the southern deposits more than the northern. It is evident that millions of tons of guano would have been necessary to produce the phosphatization.

In general, the phosphatization appears to have affected blocks and boulders that had fallen off or split from the granite and porphyry of the hills. The Kreefte Baai deposit lies on an almost holocrystalline granite with little ground substance, the Oude Post deposit on granite-porphry with a considerable amount of stony ground substance which is

apparently more easily phosphatized than is the macrocrystalline rock. Evidence of the complete phosphatization of feldspar and the liberation of SiO_2 was obtained in section. In one specimen, from near the base of the deposit, there appeared to be evidence of replacement of already formed phosphate by chalcedony. Secondary enrichment in calcium near the base of the deposit (VI, VII) along the old beach also occurred. Some of the phosphate is regarded by Du Toit as colloidal and some is compared to the barrandite described by Lacroix from Ihleu das Cabras, San Thomé (p. 315). Du Toit, as has just been indicated, believes that in general the phosphate was formed by rock falling into, or becoming mixed with, guano. The mass so formed evidently could slip down the slopes

of the islands. In some places lenticular masses of white porcellanous rock are believed to have been produced by phosphatization of a clay formed by decomposition of the bed-rock. Where large boulders were included in the guano, the inner part remained unphosphatized. Analyses are given in table 13.

South African coast stood higher than it does today and that the littoral molluscan fauna of the west coast of South Africa then consisted either of species now extinct or of species now living in the warm coastal waters of the southeastern South African littoral (Haughton, 1932). The shore line of this time

TABLE 13

	I	II	III	IV	V	VI	VII	VIII
H ₂ O at 110°C.	—	—	—	8.06%	3.56%	7.15%	6.89%	4.16%
Al ₂ O ₃	16.11%	14.48%	17.29%	8.44	2.60	9.31	5.32	4.18
Fe ₂ O ₃	9.21	8.71	8.73	3.36	11.96	2.60	2.64	2.82
CaO	1.09	1.71	3.06	2.14	2.08	5.78	6.26	0.42
Na ₂ O	—	—	—	—	—	—	—	3.74
K ₂ O	—	—	—	—	—	—	—	5.48
P ₂ O ₅	27.24	28.11	32.63	10.08	17.08	18.10	12.23	9.70
SiO ₂ and insol.	38.94	36.71	25.12	47.62	49.29	45.51	52.87	77.05

I-III. Constable Hill.

IV. Kreefte Baai, lenticular white mass of phosphatized clay.

V. Kreefte Baai, dull greenish brown.

VI. Kreefte Baai, phosphatized beach deposit at bottom of section.

VII. Kreefte Baai, white phosphate from same region.

VIII. Kreefte Baai, partially phosphatized boulder.

The alkalis in VIII (table 13) are mainly not acid soluble, but 1.018% Na₂O and 0.174% K₂O dissolved. It is supposed that the sodium in particular was included in the phosphate, but in what form is not clear. The first three analyses are supposed by Du Toit to represent a mixture of siliceous matter and barrandite. If it is assumed that the undetermined material of these analyses represents water, they become:

	I	II	III
H ₂ O	12.13%	16.25%	17.60%
Al ₂ O ₃	26.39	22.89	23.10
Fe ₂ O ₃	15.08	13.75	11.66
CaO	1.79	2.70	4.09
P ₂ O ₅	44.60	44.41	43.60

analyses that can be compared with those of similar phosphatized igneous rocks in many other parts of the world. As is indicated in the general discussion (p. 476) of this matter, the supposed water contents are too low but the ratios of P₂O₅ to (Al,Fe)₂O₃ are in good accord with that in barrandite, (Al,Fe)PO₄·2H₂O.

It is known that in late Tertiary or early Pleistocene times the relative sea level of the

has been disturbed by earth movements, but two subsequent periods of sea level higher than the present can be recognized (Krige, 1927; Haughton, 1932; Cooke, 1941). The older major transgression (phase D of Haughton) led to the formation of beaches usually now about 18 to 20 meters (50–60 feet) above modern sea level. Some warm-water mollusks are associated with these beaches. The second or minor transgression (phase B of Haughton) led to formation of beaches about 6 meters (20 feet) above modern sea level. At the time that Du Toit described the Saldanha Bay phosphate deposits it was believed that these beaches from 20 to 6 meters represented a continual fall in sea level, but it is now known that a phase of emergence (phase C of Haughton) separated the two transgressions. The aluminum phosphate deposit is therefore presumably to be associated with the major transgression, the phosphatized shell breccia with the minor transgression or perhaps with a still lower series of raised beaches at about 4 meters (12–14 feet) which constitute Haughton's phase A, though the capping of *Dorcasia* limestone is probably evidence against the latter alternative.

There is as yet no full agreement on the dating of these events. It is certain (Cooke, 1941; see also summary *in* Pickford, 1937) that the minor transgression occurred at some time when South Africa was inhabited by men making Middle Stone Age artifacts. The minor transgression may therefore be referred to a date not older than the late Pleistocene. There is some evidence (Cooke) that the major transgression occurred prior to

phosphate layer appears to lie about 100 feet above sea level. Frankel found that most nodules, which have a resinous luster, are composed mainly of fluor-apatite. One nodule, which had the appearance of unglazed porcelain, showed a lower F:PO₄ ratio than the others and may have contained hydroxyl-fluor-apatite and (Al,Fe)PO₄. No lines of variscite, however, were found in the X-ray powder diagram.

	GREENISH CLAY	NORMAL NODULE		PORCELLANOUS NODULE	
		WHITE CRUST	BROWN INTERIOR	WHITE CRUST	BROWN INTERIOR
SiO ₂	35.8 %	14.3 %	3.9 %	8.03%	—
TiO ₂	0.3	0.1	0.1	—	—
Al ₂ O ₃	9.1	5.8	3.1	2.28	3.44%
Fe ₂ O ₃	4.6	2.1	7.7	1.18	6.64
MgO	tr.	tr.	nil	tr.	tr.
CaO	23.4	41.9	44.7	42.02	41.11
P ₂ O ₅	14.3	27.6	27.9	36.0	35.0
H ₂ O+	4.21	1.05	4.51	3.22	4.25
H ₂ O—	5.19	2.45	1.79	2.52	1.68
CO ₂	2.10	3.0	6.4	1.8	2.1
F	1.4	2.5	2.5	2.2	2.45
SO ₃	—	0.60		—	—

the entry of the makers of the Stellenbosch artifacts, large coup-de-poigns of a relatively early paleolithic type. Cooke therefore regards the major transgressions as having occurred during the middle Pleistocene. Correlation of the sea levels with the pluvial periods of Africa and with the glacial periods of Europe has been attempted by various authors (older work summarized by Pickford, 1937; Cooke, 1941; Zeuner, 1945), but no agreement has been reached.

Another occurrence of phosphate in the southwestern Cape Province has been reported from Langebaan Road (Haughton, 1933; Frankel, 1943). Here the material consists of nodules, brown internally and with a white crust, in a greenish, partly phosphatized clay, overlain with sand and silcrete. The

Haughton states that a nodule analyzed for him indicated that the interior contained less P₂O₅ than the superficial layer, but this is not demonstrated by Frankel's analysis.

Haughton believes the Langebaan Road phosphate to have been a lagoon deposit, the P₂O₅ having been derived from guano on islets in the lagoon. He states that an analogous lagoon, cut off from the sea by a sand bar, encloses the modern guano islets at Cape Cross in southwest Africa. It is unfortunate that no information exists that enables the Langebaan Road deposit to be dated. Another deposit of phosphatized calcareous sand, lying under modern sand, exists on the old coastal plain at Mamre, Darling Division, Cape Province (Union of South Africa, Geological Survey, *in litt.*).

PHOSPHATIC GUANO ON THE NORTHWEST COAST OF AFRICA

There is a region of upwelling along the northern part of the western coast of Africa, along which the Canary Current flows. Higher phosphate concentrations than in the open ocean and a concentration of phytoplankton are known in this region (Hentschel,

1928). Moreover a long stretch of the coast line is very dry, so that if there were suitable islands considerable deposits of guano would be expected. Only two guano bearing or phosphatized islands are, however, recorded, and these lie somewhat south of the optimal

region either climatically or oceanographically.

In addition to the localities described there is a little fragmentary evidence of very small quantities of guano occurring on some of the other islands of the North Atlantic. According to the British import statistics (Great Britain, Parliamentary Sessional Papers, Trade and Navigation), the following quantities of guano were imported into Great Britain:

Azores, 1850-1856	517 tons
Canary Is., 1851	135 tons

According to the United States Statistics (Annual Reports on the Commerce and Navigation of the United States, U. S. Bureau of Statistics), the following quantities of guano were brought from such islands into American ports:

ISLAND	YEAR	TONS	DOLLARS
			PER TON
Azores	1866	1	\$42
Cape Verde	1865	200	\$ 8
Cape Verde, Madeira, and Azores	1866	300	\$15

The Cape Verde Island material was evidently very inferior. The islands are dry and barren and have bird colonies. Simmons (1927) figures a colony of *Sula l. leucogaster* on Corral Velho, and also the nesting site of a petrel, presumably *Oceanodroma c. castro* Harcourt, on Cima, and an extraordinary cemetery of these birds on the same island. It is not clear from the available accounts why the Cape Verde Islands produced so little guano.

ALCATRAZ ISLAND

LATITUDE 10° 38' N., LONGITUDE 17° 41' W.

A small island in a group of reefs, off the coast of French Guinea. The island was known as a source of guano in the last century. Meise indicates that an account of the island was given by Bouteiller whose work it has not been possible to consult. A more recent account has been given by de Chélat (1938). The island is about 90 meters in diameter and has an area of 8000 m². Its maximum elevation is about 8 meters above sea level. The emergent part is composed of a layer of laterite 4 meters thick capped with 2

to 3 meters of phosphatic guano. The laterite immediately below the guano is ferruginous, the lower laterite paler and clay like. The guano is evidently formed by a flourishing colony of *Sula l. leucogaster* noted by Meise, presumably from Bouteiller, and well shown in de Chélat's photographs. The superficial material derived from bird droppings and fish remains is pulverulent and contains mummified dead chicks. A few centimeters below the surface the material becomes brown, somewhat consolidated, and with concretions of calcium phosphate.

No analyses appear to have been published though de Chélat collected material of the guano and underlying laterite for this purpose. The strong seas and rains are said to remove all the soluble material so that the bulk of the guano layer must be leached phosphatic guano.

Exploitation is apparently carried out on the basis of the annual yield, fine powdery guano being collected. An interesting method of working the deposit is used, which might be applied elsewhere. Depressions are made in the surface of the island into which the materials, dissolved or loosened by the rain, are carried. On evaporation, the depressions are left containing a guano richer in nitrogen than can otherwise be obtained.

ILE DE CORAIL, LOS ARCHIPELAGO

LATITUDE 9° 28' N., LONGITUDE 13° 50' W.

Off French Guinea; in spite of its name, apparently in part at least composed of eruptive rock. Superficial phosphatization, undoubtedly due to the action of guano solutions, occurred in a way comparable to that occurring at Clipperton Island and at various West Indian localities described below. Lacroix (1911) describes the altered rock as showing faint traces of the original phenocrysts and as containing fragments of clastic quartz. The bulk of the material was transformed into a substance that appeared to be amorphous and gave on analysis:

H ₂ O	23.60%
Al ₂ O ₃	25.39
Fe ₂ O ₃	6.50
FeO	1.20
MgO	0.24
CaO	2.12

Na ₂ O	1.06
K ₂ O	tr.
TiO ₂	1.10
P ₂ O ₅	33.54
SiO ₂	5.25

Lacroix termed this material redondite, a term originally applied to a comparable phosphate from Redonda in the West Indies. It

is, however, virtually certain that Lacroix's redondite does not really differ from variscite, $\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$, and barrandite, $(\text{Al}, \text{Fe})\text{PO}_4 \cdot 2\text{H}_2\text{O}$, in being amorphous, and the name barrandite is probably the correct designation of this material from the Los Archipelago, as well as from the other localities to be discussed (pp. 475-477).

PHOSPHATIC GUANO ON THE ATOLLS OF THE PACIFIC OCEAN

THE LEACHED GUANO DEPOSITS on a number of more or less elevated atolls (fig. 45) in the Pacific Ocean have been and continue to be important sources of phosphate. They present, moreover, a number of purely scientific problems of extraordinary interest. In a discussion of these islands it has proved convenient to consider first the area of the central Pacific, on some of the islands on which phosphate guano is now, or was in the last century, still being deposited. The Hawaiian Leeward Islands and Clipperton Island, the only atoll in the eastern Pacific, must each be treated separately. A large number of phosphatized islands exist in the western Pacific, north of the Equator. Here contemporary phosphatization is of little importance.

In addition to the slightly elevated atolls bearing phosphatic guano, there are certain raised coral islands which have undergone very extensive phosphatization at a relatively remote time, though they lie in regions not now characterized by modern deposits. Such

islands occur in the Tuamotu group, south of the region of modern phosphatization, in the equatorial region to the west of the area of modern guano islands, and in various parts of the western Pacific, north of the Equator. The geographical subdivisions to be adopted in presenting the data on the Pacific islands are therefore as follows:

- Slightly elevated atolls in the central Pacific
- An atoll in the eastern Pacific
- The Hawaiian Leeward Islands
- Raised phosphatized atolls in the Tuamotu group and elsewhere in the South Pacific
- Raised phosphatized atolls in the equatorial central Pacific (Nauru and Ocean Islands)
- Raised phosphatized atolls and other islands in the western Pacific

The arrangement is admittedly artificial. It is, for example, not possible to draw a clear distinction between some of the slightly phosphatized Tuamotu Islands and the southernmost islands of the group first named.

SLIGHTLY ELEVATED ATOLLS OF THE CENTRAL PACIFIC

The most important of the slightly elevated atolls bearing phosphate are certain of the scattered islands known to cartographers as the central Polynesian Sporades and to mariners as the Line Islands, and the more compact group of the Phoenix Islands. With these may be considered Johnston Island, Flint Island, and Caroline Island, and two occurrences of guano in the Marquesas Archipelago. The best general description of these islands is to be found in Bryan's (1942) invaluable work on American Polynesia. It must be remembered that certain islands have now become important air bases and that numerous changes in ecological conditions must have occurred recently on such islands. These changes are not relevant to the present discussion.

OCEANOGRAPHY

The ocean circulation of the central Pacific is of great interest in relation to the distribution of guano islands. The data available are not so complete as might be desired; they have recently been admirably summarized by

Sverdrup, Johnson, and Fleming (1942; cf. Graham, 1941). The South Equatorial Current flows to the west on both sides of the Equator, while the North Equatorial Current flows with its southern margin north of about latitude 10° N. Between these two westwardly directed currents, there is a narrow but well-marked Equatorial Counter Current flowing eastward between latitudes 5° and 10° N. Chemical data obtained during the last cruise of the "Carnegie" (1928-1929), for the equatorial region about longitude 140° to 150° W., clearly indicate the transverse movements that are superimposed on the main circulation. Along the southern boundary of the Equatorial Counter Current, in about latitude 5° N., there is a marked sinking of surface water, while at the northern border of the counter current and on the southern border of the equatorial current, there are marked upwelling and divergence, indicated by low oxygen concentrations and high silicate and phosphate concentrations in the immediate subsurface water. These chemical in-

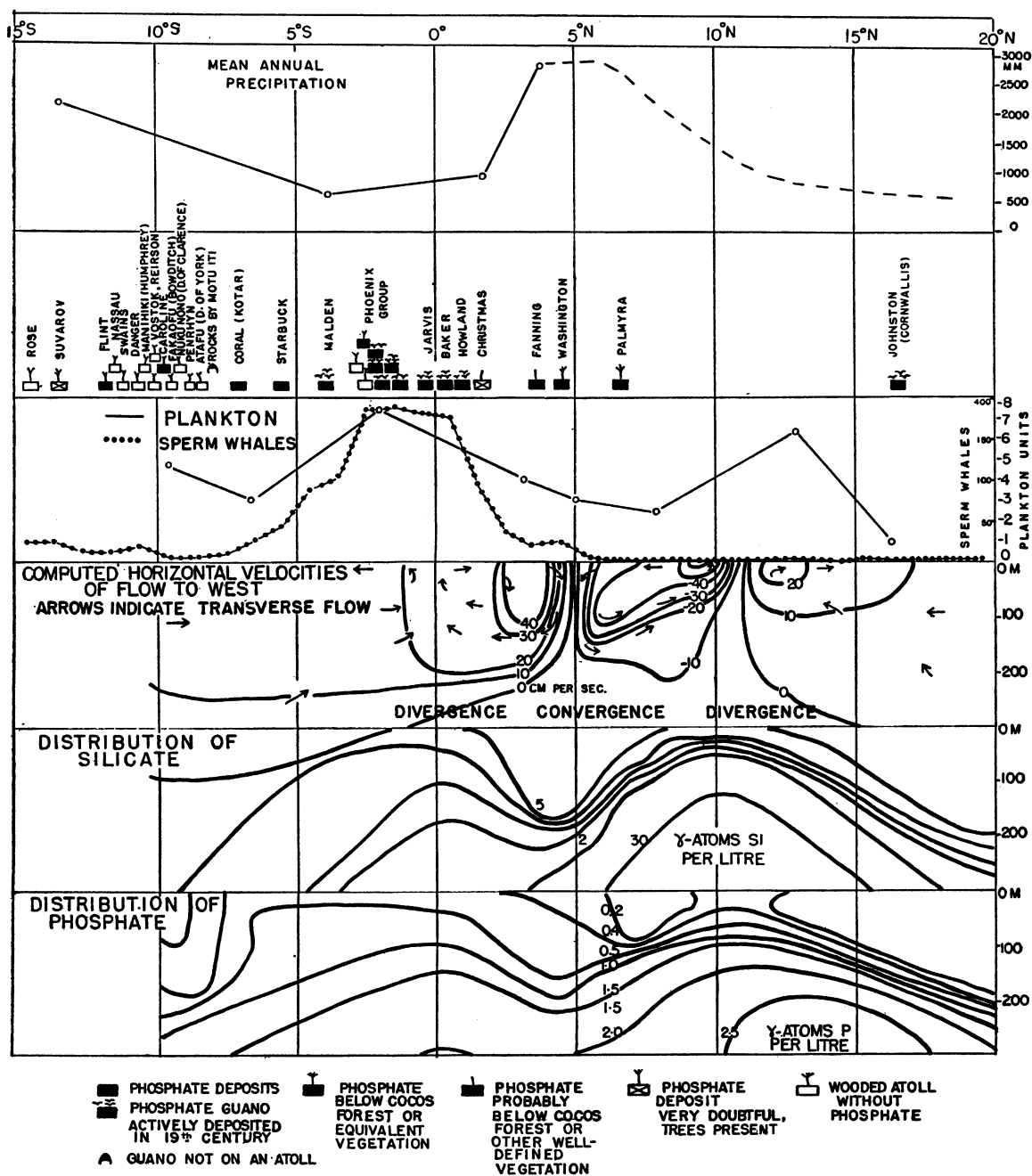


FIG. 46. Section of the Pacific, from longitudes 140° W. to 180° W., projected onto a plane, showing distribution of rainfall, guano islands, plankton (in arbitrary units, after Graham), sperm whales (kills recorded in nineteenth century log books, after Townsend), circulation, silicate, and phosphate (after Graham).

dications of upwelling along the divergences are reflected in plankton maxima in about latitude 13° N. and 2° S., with a marked minimum between latitudes 5° N. and 8° N. (fig. 46).

The maps prepared under the direction of C. H. Townsend (1935) demonstrate that the nineteenth century whalers obtained an enormous number of sperm whales in a belt running from the South American coast across the Pacific to about longitude 161° E. This belt lay approximately between latitudes 2° N. and 4° S. It therefore includes the divergence and high-plankton zone discovered on the last "Carnegie" cruise. There can be little doubt that this equatorial whaling ground, called by the whalers "On the Line," is related to the upwelling in the divergence. There is an indication that within the zone of abundant whales, a minimum in the population occurred between longitudes 140° and 150° W., but throughout the region of the Line and Phoenix Islands the zone was very productive at all seasons. It is interesting to note that there is no corresponding development correlated with the northern divergence in latitude 11° N. This, and the fact that both plankton and surface phosphate contents are slightly lower in the northern than in the southern divergence, suggest that the northern divergence is biologically less important than the southern.

CLIMATOLOGY

The equatorial wet belt runs across the Pacific just north of the Equator. To the north and south of the wet belt are regions of lower precipitation, extending westward from the coast of Mexico and of South America. In these drier regions the rainfall increases irregularly from east to west. South of the southern subequatorial dry belt a wet region extends from New Guinea eastward towards Tahiti. In the region of longitude 165° W., the "Atlas of climatic charts of the oceans" (McDonald, 1938) indicates that steady rain may be expected in over 5% of observations at Greenwich Mean noon between latitudes 2° N. and 14° N., and in over 10% of observations between latitudes 4° N. and 8° N. In the region between longitudes 156° and 175° W., as is clearly indicated in Bryan's (1942) map, we therefore find Johnston Island in a rela-

tively dry belt, the northern Line Islands in a wet belt, the southern Line Islands and most of the Phoenix Islands, on which the principal commercially significant phosphate deposits occurred, in a relatively dry belt, while Samoa (mean annual precipitation at least 2280 mm.) and the Cook Islands (mean annual precipitation at least 2100 mm.) and certain adjacent atolls without phosphate deposits lie in another wet belt.

The three northern Line Islands, namely, Palmyra, Washington, and Fanning, are well covered with groves of *Cocos*, *Pisonia*, and *Tournefortia*; Washington Island has a bog and fresh-water lake replacing the lagoon. Extensive meteorological data exist only for Fanning Island, where the mean annual precipitation is 2733 mm. (Christophersen, 1927) distributed very irregularly both with regard to season and from year to year. Palmyra probably has a similar climate, while Washington is somewhat wetter. Hunt (1914) gives data for July, 1910, to February, 1911, inclusive, during which period Fanning received 418 mm. of rain and Washington 860 mm. Christophersen, over a very short period, found but 10% more¹ precipitation on Washington than on Fanning.

Christmas Island is considerably drier than these three islands; its vegetation consists mainly of a number of scrub communities (Christophersen, 1927). Reed (1927) gives 950 mm. as the mean annual precipitation between 1916 and 1919, but indicates much higher values in 1903-1905, the sum of the incomplete data for the latter year reaching the fantastic figure of 7571 mm. The evaporating power of the air on Christmas Island was found by Christophersen to be about 287 cc. per week from a porous cup atmometer. Such a value is characteristic of semi-desert regions. On Jarvis Island the evaporating power was found to be about half as much again as Christmas Island, while in the coconut forest of Washington Island very reduced values were obtained, though in exposed situations the values were comparable to those observed on Christmas Island.

Jarvis, Starbuck, Malden, Howland, Baker, and the Phoenix Islands, lying to the south of these wetter atolls, fall in a very dry belt.

¹ Not 10% less as Wentworth (1931) says.

Their vegetation consists of a limited number of xerophilous herbs and grasses, which may form simple communities as on Baker and Howland Islands but which on Jarvis Island "are strewn over the flat as if by accident" (Christophersen, 1927). Save in the case of Malden Island, there is little quantitative meteorological information available about these dry islands. Ramsey (1925) doubts that Howland has a mean annual precipitation of over 77 mm. When irregular rains occur on the drier islands they may be torrential. Writing of Jarvis Island, which from its vegetation appears to be the driest of the group, Closson (1893) describes rain as "almost solid . . . in . . . sheets of water for hour after hour."

The climate of Malden Island is moderately well known. In general it is arid, but very irregular and often violent rains occur. In 1867 there were but 12 wet days (Dixon, 1878a), delivering 33.4 mm. of rain. In 1868 there were 52 wet days, delivering 345 mm. of rain; on three of these days more than 44 mm. fell. In the first three months of 1869, 28 wet days delivered 514 mm., and of this 116 mm. fell in a single downpour lasting eight hours. More recent meteorological observations, from 1891 to 1918, indicate a mean annual rainfall of 653 mm., the annual precipitation varying from 100 mm. in 1908 to 2377 mm. in 1914 (Clayton, 1927; Reed, 1927). The rainfall, though so irregular, shows a strong seasonal variation, the greater part occurring during the first half of the year. The mean annual precipitation is thus probably less than on Christmas Island and even more irregular. A single observation on evaporation in December, 1868, gave a mean value of 9.84 mm. per day.

There are some fragmentary data for the rainfall on Hull and Sydney Islands in the Phoenix group, and for Flint Island which lies south of any of the other islands so far considered (Hunt, 1914):

ISLAND	DATE	AN- NUAL MEAN MM.
Hull	May 1, 1903-June 30, 1905	1820
Sydney	Feb. 13, 1904-June 30, 1905	1670
Flint	June 1, 1903-Sept. 30, 1905	1472

It is most improbable that the first two of

these figures give a true idea of the mean annual precipitation in the Phoenix Islands, for 1905 seems to have been an abnormally wet year. The extraordinary rainfall on Christmas Island has already been mentioned. Moreover, on Malden Island, 1905 was the second wettest year noted between 1891 and 1918, and of the 1966 mm. recorded in 1905, on that island, 1582 mm. fell before the end of June and so within the period of observation on Hull and Sydney Islands. The Malden record lacks data for February, 1904, but if it were used from March 1, 1904, to June 30, 1905, to correspond approximately to the Sydney data, it would give a mean annual precipitation of 1533 mm. for Malden instead of 653 mm. Whatever the true mean annual precipitation on Phoenix and Hull Islands may be, it is apparent from their vegetation that these two islands, with Gardner Island, are somewhat less arid than the other five members of the group. The vegetation of Flint Island, now almost entirely given over to coconut plantations, indicates, however, that the value given above for this island is unlikely to be too low.

The mean annual temperature and the range of extreme temperatures are given by Reed (1927) as follows:

ISLAND	LOWEST	HIGHEST	MEAN
Fanning	21.1° C.	37.8° C.	28.0° C.
Christmas	22.8	41.1	—
Malden	18.3	36.1	27.9

Christmas Island may possibly be somewhat warmer than the other two islands; it is, however, unlikely that any great variation in mean temperature occurs from island to island.

Dixon states that the temperature on Malden Island normally varied from 26.7° C. at daybreak to 35.6° C. between about 10:00 A.M. to just after sunset. Occasionally, at the time of heavy rain, the temperature fell to 25° C. Under 2.5 cm. of light gray soil the temperature rose to 51.7°-57.2° C. in the afternoon.

ORNITHOLOGY

The most important contributions to the ornithology of the Pacific guano islands are those of Lister (1891) and Buddle (1938; see also Bryan, 1940) on the birds of the Phoenix Islands, and of Streets (1877a, 1877b) and of

Kirby (1925) on those of the Line Islands. Additional information can be obtained from Ellis (1937) and from the older accounts of Dixon on Malden Island, and Hague on Baker, Howland, and Jarvis Islands, though their specific identifications are worthless.

From these sources it is clear that on the drier barren islands in a natural condition the commonest breeding birds were terns. Hague speaks of breeding colonies of millions of terns covering acres of ground on Baker Island; Dixon likewise of five acres being occupied by the tern colony on Malden Island. Lister found thousands breeding in June and July on Phoenix Island, where they were clearly the commonest birds. Ellis "never ceased to marvel" at their numbers on Hull Island. A colony of *S. fuscata oahuensis* Bloxham is apparently still present in the northeastern part of Jarvis Island (Christophersen, 1927), though the bird is not mentioned by Kirby. Beck (1921) likewise mentions a large colony on the northeastern side of Christmas Island. Streets notes a very populous colony breeding just above high-tide mark at the extreme eastern tip of Washington Island, while Rock (1916) describes a large colony nesting on bare coral rock or sand on the extended shore of Bird Islet, Palmyra. From Lister's account and from the general distribution of terns in the Pacific (Mayr, 1945) it appears that *Sterna fuscata oahuensis* Bloxham and *Sterna lunata* Peale are the two most abundant species on the barren islands. Lister says that on Phoenix Island they occupy separate areas but are about equally common. The tern colonies are easily disturbed. On Howland Island, which appears to have been occupied by man at some time prior to its discovery by European navigators, Pacific rats, *Rattus r. exulans* Peale, were extremely numerous, and Hague believes that this may account for the absence of a colony, though Ellis mentions terns and great numbers of frigate birds. He says, however, that rats, apparently from a wreck, had destroyed the bird colony on Baker Island. The Malden colony was being decimated by feral domestic cats during Dixon's visit. Several other species of terns are recorded by Buddle (1938).

The noddy, *Anous stolidus pileatus* (Scopoli), is probably the next most abundant bird on undisturbed barren islands, but no

observer writes of its numbers in the same terms as are used for the terns or "wide-awakes."

When a continuous vegetation cover develops, as on the less arid northern members of the Line Islands, colonies of the genus *Sterna* are confined to littoral bare areas of sand and broken coral; such colonies on Washington and on Palmyra have already been noticed. Under these conditions, it is very improbable that any permanent accumulation of guano would take place, as the rainfall is heavy and the slope of the beach would lead to loss of material into the sea.

On the more richly vegetated islands, noddies frequently nest in trees, but they may be seen standing at rest in large, compact flocks under conditions which might perhaps be more favorable for accumulation of guano, though in most cases the deposit would probably be washed away. On the wetter islands certain other terns are also found. *Gygis alba candida* Gmelin breeds in trees and bushes on Washington, Fanning, and Palmyra. Streets found this species breeding on coral blocks on Christmas Island, but Kirby says that *Tournefortia* branches are preferred. Lister found *Gygis* breeding on bare coral rock on Phoenix Island, but Kirby implies that the absence of this bird on Jarvis may be due to lack of trees or tall bushes. *Anous minutus melanogenys* G. R. Gray on Fanning and Christmas and *Procelsterna cerulea* (F. D. Bennett)¹ on Fanning are apparently entirely arboreal in their nesting habits. Thus although terns are common on all the islands, there is some progressive substitution as well as change of habits in passing from the dry barren to the richly vegetated, humid islands. Only on the former are the great colonies that could form relatively pure guano deposits likely to be present.

Boobies are extremely common. In general *S. leucogaster plotus* Forster and *S. dactylatra personata* Gould, which breed on the ground, are commoner on the barren islands, but they both nest on Fanning and at least the latter on Washington and Palmyra,² though it

¹ The subspecific determination of the birds on Fanning Island seems uncertain. On the Phoenix Islands *P. c. nebouxii* Mathews is recorded (Peters, 1934).

² Rock's statements about the boobies on Palmyra are confused; all three species are noted. "The large blue billed Booby (*Sula piscator*)" is said to be the com-

is not common. On Canton Island *S. d. personata* is known to be the commoner of the two, but it is possible that *S. leucogaster plotus* was the most important guano bird on Howland in the virgin condition. On the more vegetated islands, *S. sula rubripes* is vastly commoner, being the most abundant of all birds on Fanning Island. This is easily understood, as *S. sula* nests almost invariably in trees or bushes. An exception to this habit appears to be provided by the population on Jarvis Island, where Kirby found the species piling up sticks to form low artificial bushes as nests. Hague speaks of a variety of booby with this habit on Howland Island, which probably refers to the same species, though on Howland *Cordia* trees are present and *S. sula* probably occupies them. It is difficult to assess the contributions to the guano deposits by boobies. It is possible that originally they were the chief guano birds, but that now their contribution to such guano as is deposited is less than that of terns. If the document in the Mystic Marine Historical Society, discussed below, can be trusted on this matter, a booby, probably *S. leucogaster plotus*, was the chief guano bird on Howland before occupation by guano diggers. Photographs of the nests of *Sula* on the islands give little indication of accumulation, though at Howland there is evidence of guano deposition in the stunted *Cordia* bushes.

Both Dixon and Hague regard the man-o'-war bird, presumably *Fregata minor palmerstoni* Gmelin, as a significant contributor to the guano deposits. Buddle says that it is the most numerous species breeding on Canton. The very conspicuous nature of the man-o'-war bird, which forms striking breeding colonies, may overemphasize its role as a guano bird.

In addition to these species, Lister records

monest; other species are "not at all numerous. One *Sula sula*, is of a brownish color with black bill; it roosts in company with *Sula piscator* in Tournefortia branches and lays one egg, while the other species *Sula cyanops*, rather rare, has black and white plumage, . . . and lays usually two eggs on the bare sand." If the nomenclature current in literature on the central Pacific at the time be accepted, *Sula piscator* equals *S. sula rubripes*, *S. cyanops* equals *S. dactylatra personata*, *S. sula* equals *S. leucogaster plotus*. The statement seems to imply that the last species breeds on Palmyra, in trees, which is most improbable.

Nesofregatta albigularis (Finsch) and *Pterodroma alba cantonia* Mathews (sub *Oestralata parvirostris*) as present in numbers on Phoenix Island. Buddle adds *Puffinus lherminieri dichrous* Finsch and Hartlaub on Canton. Dixon considers that a "mutton-bird" (presumably either *Puffinus pacificus chlororhynchus* Lesson or *P. nativitatis* Streets) is of some significance as a guano bird on Malden. The red-tailed tropic bird, *Phaeton rubricauda* (Boddaert),¹ is also widespread through the islands, breeding on the ground, and is a possible contributor to guano. *Phaeton lepturus* Daudin is more arboreal in its breeding habits and is less likely to make any permanent contribution. The goney, *Diomedea nigripes* Audubon, occurs only at Johnston Island and is the sole albatross found in the region.

It is reasonable to suppose that not only is freshly deposited guano more easily eroded on the wetter islands, but that forest vegetation may establish itself and make the island unsuitable for large colonies of ground-breeding sea birds, that in fact *Pandanus*, *Pisonia*, and coconut palms may directly and successfully compete with ground-nesting boobies and sooty terns for the limited available space. Such an interpretation was put forward by Hague (1862). Where large numbers of arboreal species occupy an island, phosphatic soils are probably always developed, but such evidence as is available, notably from Rose Atoll, indicates that neither workable guano nor significant phosphatization of consolidated coral rock occurs on such islands.

Miss Patricia M. Ralph and a party of New Zealand biology students most kindly made systematic ornithological observations on a voyage from San Francisco to Auckland. Three or four albatrosses were observed daily for the first five days of the voyage. On the sixth day (noon, latitude 14° 44' N., longitude 147° 29' W.) no birds were seen. On succeeding days (noon, latitudes 9° 45' to 00° 23' N., longitudes 151° 51' to 160° 24' W.) *Phaeton* and small species of oceanic birds were observed at a distance. No birds were observed south of latitude 5° 47' S. Though many records are needed to elucidate the equatorial pattern, these observations

¹ The subspecies of *Phaeton* do not appear to be adequately elucidated.

clearly indicate the paucity of birds in the southern part of the tropical Pacific Ocean.

The islands on which there is reasonably clear evidence of the existence of very great bird colonies, actually producing guano at some time during the nineteenth century, are Malden, Jarvis, Baker, Howland, and the Phoenix group. Starbuck probably should be included with these islands, all of which yielded important commercial quantities of phosphate. All these islands lie between latitudes 00° 49' N. and 5° 37' S., on either side of the southern divergence and its associated plankton maximum in latitude 2° S., and within the whaling ground "On the Line."

A few notes on the non-marine birds of the islands may not be out of place here, as reference will be made to the matter at a later point in the discussion. A parrot, *Vini kuhlii* (Vigors), which though observed in 1798 by Fanning, who records this "most beautiful and lovely bird," appears to have been introduced into Fanning and Washington Islands prior to the end of the eighteenth century. According to Peters (1937; cf. Amadon, 1942) the original home of the species is Rimitara, in the Austral Islands, a fact of considerable archaeological interest.

The only true native land birds now occurring on any of the Line Islands are subspecies of the endemic warbler *Conopoderas aequinoctialis* (Latham). The typical *C. a. aequinoctialis* occurs on Christmas Island; *C. a. pistior* (Tristram) lives on Fanning Island; while a third inadequately known but probably different race inhabits Washington Island (Murphy and Mathews, 1929). It seems virtually certain that no warbler or other land bird occurs on Palmyra. *Conopoderas* belongs to the family Sylviidae, or Old World warblers, and is a characteristic member of the fauna of the more vegetated central Pacific islands. In addition to the warbler, a remarkable duck formerly frequented the fresh-water lagoon of Washington Island. This duck, *Anas streperus couesi* (Streets), was a dwarf subspecies of the circumboreal gadwall, differing not only in size but also in beak structure. It is known only from two immature birds collected in 1874; subsequent to that year it apparently became extinct, doubtless as a result of duck hunting by settlers who did not recognize the Coues gadwall as a resident

form distinct from migratory ducks that visit the lagoon (Wetmore, 1925a). A pintail, described as *Dafila modesta* Tristram, has similarly been supposed to have been confined to the lagoons of the Phoenix Islands during the last century and is still mentioned in some recent papers, though Salvadori (1895) casts great doubt on its validity, and Peters (1931) and Delacour and Mayr (1945) omit it altogether from their lists.

DESCRIPTION OF THE ISLANDS

In view of the striking climatic zonation discussed above, it has proved convenient to discuss the individual islands in the following order:

Dry islands undergoing phosphatization at the time of their discovery—Howland, Baker, Jarvis, the Phoenix group, Malden, and Starbuck Islands

An intermediate, almost unphosphatized island—Christmas Island

Wet islands to the north—Fanning, Washington, and Palmyra Islands

A dry island north of the equatorial rain belt—Johnston Island

Wet islands to the south—Caroline and Flint Islands

To these groups may be added notes on:

Doubtful and apocryphal guano islands

Atolls without phosphatic deposits, of comparative interest

Phosphatic soils on Rose Atoll

DRY ISLANDS UNDERGOING PHOSPHATIZATION AT THE TIME OF THEIR DISCOVERY

HOWLAND ISLAND

LATITUDE 00° 48' N., LONGITUDE 176° 38' W.

An elongate, slightly raised atoll with a dry lagoon, about 2400 meters long and 800 meters wide (fig. 47). The highest point of the atoll rim is 5.2 meters (17 feet) above the circumlittoral coral platform and 3.0 to 3.7 meters (10 to 12 feet) above high-tide mark. The vegetation was somewhat better developed than on Baker Island when Hague visited the two islands, but Christophersen's account does not, save in one respect, suggest any great difference in the general development of the plant cover today, though the flora list of five species on Howland is far less extensive than that of

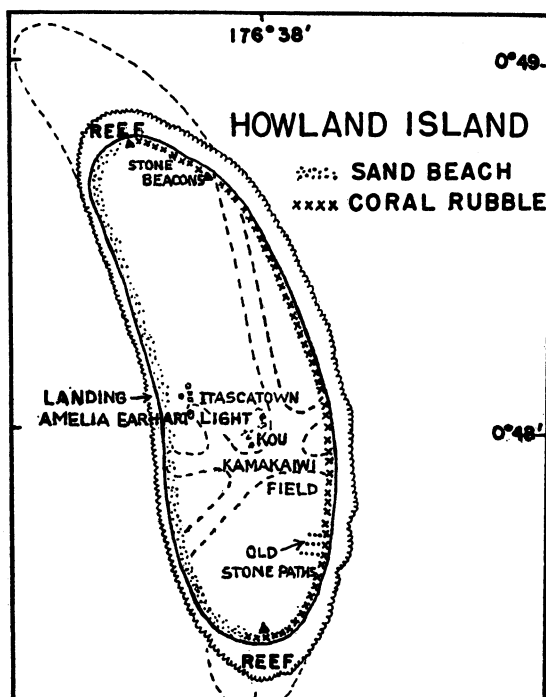


FIG. 47. Map of Howland Island. After Bryan.

Baker Island. The most curious feature of the vegetation of Howland is the presence of five groves of Kou trees (*Cordia subcordata* Lamarck). These trees reach a maximum height of 5 meters and a maximum diameter of 50 cm. They are crooked and much branched. Many are dead at the top, and about one-third of the wooded area consists of dead trees. Flowers and fruits are commonly produced, but no reproduction from seed seems to occur. This condition appears to have persisted for at least 68 years, from the time of Arthur Benson's visit in 1857 to 1925 when Christophersen examined the island. The *Cordia* thickets are associated with artificial depressions and mounds (Hague, 1862). The depressions are comparable to excavations used for cultivating taro and other plants in the Tuamotu Archipelago. A few enclosures, pavements, and paths exist on the island, but none indicates any place of origin or date of settlement. Black and brown Polynesian rats abound (Emory, 1934).

Hague states that the guano deposit covered most of the middle part of the island, lying on hard coral rock, and varying in

depth from 15 cm. to 1.2 meters (6 inches to 4 feet). The map published on an unnumbered sheet, "Guano islands of the Pacific ocean," by the United States Hydrographic Office and based on Commander R. W. Meade's survey of 1874 indicates a road running to the north, to a region marked in Bryan's (1942) map as old guano diggings. The best deposit may therefore have been in the northern half of the island. The shallow guano, like that of Baker Island, supported a growth of *Portulaca*. Today *P. lutea* Solander and *Boerhaavia tetrandra* Forster¹ cover most of the interior of the island, the former species being the commoner. As on Baker Island, the shallow guano with *Portulaca* was darker, coarser, and contained many vegetable fibers, while the deeper deposits consisted of a fine, damp, reddish brown material almost devoid of fibers. The analyses given in table 14 have been published.

An earlier analysis given by Drysdale (1861) in which no magnesium is recorded and the calcium is exactly accounted for by CO_2 , PO_4 , and SO_4 , is presumably inaccurate.

An interesting relationship appears to exist between certain of the guano birds, presumably red-footed boobies (*S. sula rubripes* Gould), the *Cordia* trees, and the other vegetation. Christophersen found that in the center of a *Cordia* grove, the soil profile consisted of:

	CENTI- METERS
Dead stem of <i>Boerhaavia</i> and <i>Cordia</i> leaves	12
Compact leaves and stems of <i>Boerhaavia</i> , leaves and twigs of <i>Cordia</i> , phosphatic coral fragments	10
Dark mold, becoming lighter with yellow particles, in lower part	30

He supposes that, when exploitation of the guano of the island occurred, the birds deserted their roosts in the trees, permitting undergrowth of *Boerhaavia* to develop. Later the trees were recolonized by boobies, and the bird droppings killed the *Boerhaavia*, either by covering the leaves or by acidifying the soil.

¹ This name is used following Christophersen (1927). According to a later paper (Christophersen, 1931), it seems possible that the plant in question should be called *B. diffusa* Linnaeus.

There are more data for estimating the total mass of guano of Howland Island than are available for the other islands. Unfortunately these data have proved difficult to interpret.

According to the "Report to the stockholders of the United States Guano Company" (1859) the quantity, disclosed by a survey made in 1857, was 2,867,646 tons.

The Mystic Marine Historical Society

cated 125,000 tons of guano to be present. It is not possible at the present time to ascertain whether this estimate is based on a written or oral statement. It is not consistent with a very great mean depth of material, for assuming a density between 2 and 1, the volume would be between 62,500 and 125,000 cubic meters which, with an area of 1.62 km², derived planometrically from the map given by Bryan (1942), gives a mean depth of between

TABLE 14

	Hague (1862), Shallow with Fibers	Hague (1862), Deep	Voelcker (1876)			Schucht (1900)
H ₂ O	4.12% (at 100° C.)	1.83% (at 100° C.)	10.01%	15.31%	8.95%	11.59%
Organic	22.63 (ign.)	8.65 (ign.)	5.72	7.26	6.15	11.84
CaO	36.90	42.00	43.03	39.36	43.26	40.07
MgO	1.24	2.65	6.83	4.56	6.54	1.05
SO ₃	0.58	1.33				0.48
CO ₂ alkalis, chloride, etc.	1.67	1.94				1.51 (0.51 NaCl)
P ₂ O ₅	30.80	39.65	34.21	33.35	34.80	32.30
SiO ₂ insol.	2.00	1.95	0.20	0.16	0.30	—
Fe	—	—	—	—	—	0.65

possesses a transcript of a narrative prepared by Mr. Llewellyn Howland of South Dartmouth, Massachusetts, of an earlier surveying expedition made for the Howland family in 1856. This document was constructed from fragmentary notes and oral explanations given by Mr. Howland's uncle. Mr. Howland kindly assures me that the events recorded are historic, but that the names of persons and ships were altered in preparing the account. The document indicates the enormous numbers of birds, apparently boobies,¹ on the island, and states that a careful survey indi-

3.9 and 7.8 cm. The larger estimate is more likely to be near the correct value than the smaller. Such a mean depth is not so inconsistent with Hague's observations as might at first appear, because he specifically states that the material covered the middle of the island, while the area used includes the rampart. Bryan (1942) indicates that the main diggings were in the northern part of the island so that the actual area of relatively deep guano may have been quite restricted.

According to Commander Richard W. Meade, U.S.N. (United States Hydrographic Office, 1873) in command of U.S.S. "Narragansett," visiting the island on April 2, 1872, there was an estimated reserve of 20,000 tons, while 8000 tons had been shipped in the season of 1871. For the previous shipping season from August to December, 1870, all the cargoes were recorded in The Friend of February, 1871, and the total amount removed was 7700 tons. It would appear there-

¹ They are said to have been like pelicans but smaller and darker, suggesting *S. leucogaster plotus*, but the document is not a reliable source for such details, for the rats are said to have been the ordinary brown or Norway rat though it is known that they actually were representatives of the group of Pacific rats. The Kou trees are not mentioned, though the prospect of being abandoned and having to live on raw eggs and birds is discussed, in spite of the presence of what must have been a reasonably abundant supply of firewood.

fore that at the peak of the output from Howland, a mean quantity of about 8000 tons per annum was exploited. According to Bryan the island, which had been surveyed in 1857, was not bonded until December 3, 1858, as a dispute had occurred between the rival United States and American Guano Companies. The maximum possible output during the 13 years from 1859 to 1871 inclusive would therefore be 104,000 tons, and if the 20,000 tons remaining are added, the original reserve would seem to have been not more than 124,000 tons. This value, being based on a maximal output of 8000 tons per year prior to 1872, is likely to be excessive. However, exploitation continued until 1878, though at a lower annual output, at least 4400 tons being removed in 1873 (The Friend, 1874, p. 12). On the basis of Meade's estimate, only 7800 tons should have been left for the seasons 1874-1878, yet John T. Arundel resumed work between 1881 and 1891 (Bryan, 1942), though from Ellis' (1937) account of his venture in general in these regions, the material remaining was inferior. These considerations probably indicate that while 104,000 tons may be an excessive estimate for output before 1872, 20,000 may be too small an estimate for the reserve at the beginning of that year.

The estimate of the 1856 survey in the document put together by Mr. Llewellyn Howland is, whatever the source, concordant with that derived from the data in The Friend and in Commander Meade's report. The advertised reserve in 1857 is not concordant with either of the other independent estimates, and as one may suspect that it is tinged with commercial overoptimism the lower value of 125,000 tons seems the more reasonable figure.

BAKER ISLAND

LATITUDE $00^{\circ} 13' N.$, LONGITUDE $176^{\circ} 33' W.$

A very slightly elevated atoll, about 1 mile long and two-thirds of a mile wide (fig. 48). There is a coral platform, covered at high tide, around the island; Hague's diagram indicates this to be about 30 meters wide. Within is a ring-shaped ridge rising to a height of 6.7 meters (22 feet) and enclosing the almost level interior of the island that represents the old lagoon. The western (lee) side

of the ridge was cut through in the construction of a railway, and the section disclosed an old beach formation of stratified coral fragments and sand, the maximum elevation being 4.6 meters (15 feet) above the platform. This old, lower beach can be traced inward beyond the modern sandy ridge and immediately under the guano that occupied the middle of the island. The coral floor of the interior slopes from northeast to southeast; the guano covering, which was apparently

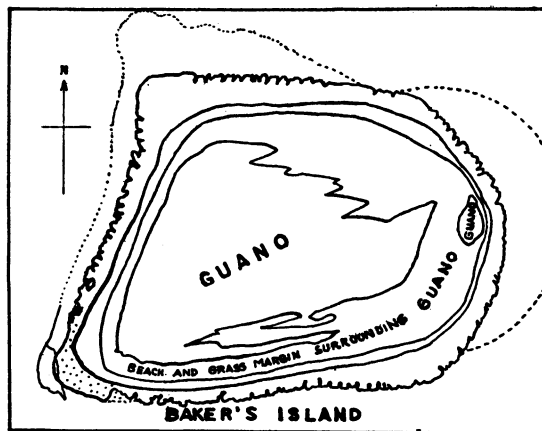


FIG. 48. Map of Baker Island. After Boggs.

level, thus varied in thickness from 12.7 cm. (5 inches) to "several feet." The shallower, drier guano supported a growth of "one or two species of *Portulaca*." At the present time a large part of the interior is covered with a mixture of *Boerhaavia tetrandra* and *Portulaca lutea*, or the former plant alone (Christophersen, 1927). The *Portulaca* may have been dominant when the guano deposits were still present; the modern vegetation may well be largely determined by their removal. The deeper guano was apparently bare at the time of Hague's visit. The shallow, dry guano on the north side of the interior was a dark brown, coarse-grained, pulverulent substance containing fine roots and fibers derived from these plants; white particles among which Liebig identified crystals of struvite occurred in it. The deeper, damper guano was less dense, of finer texture, and of reddish color. Very little crust guano occurred on the surface of the deposit; such crust as existed was found over parts of the deeper deposit and was usually thin, though occasionally up to an inch thick. Ellis (1936) indi-

cates that a remarkably hard phosphate that could be worked only by blasting occurred in a deep depression. The appearance of this material led to the recognition as phosphate rock of the first specimen brought from Nauru. A thin crust formed where pools of water had been standing after rain, and the thicker crust found only in damp places was probably produced in the same way. In some places the deposit was stratified, crusts and guano alternating, the strata being about an

based on the observation that birds were far more abundant on Baker Island. It is, however, most improbable that such hopes were satisfied. The maximal exploitation at Baker Island evidently occurred between 1866 and 1872. The total output for some of these years can be ascertained from notes in *The Friend*. For the season July, 1869 to February, 1870,¹ 11 vessels removed 12,252 tons (one was lost by fire at the island; its cargo is included). For the season for May,

TABLE 15

	Hague (1862), Fresh <i>Fregata</i> Excreta	Nesbit (1860)	Hague (1862), Dark Shallow Guano	Hague (1862), Red Deep Guano	Hague (1862), Crust Guano	Voelcker (1876)			Schucht (1900)
						Unusu- ally Rich	Good Average	Poor	
H ₂ O	10.40 % (at 100°C.)	7.30 %	1.82 % (at 100°C.)	2.92 % (at 100°C.)	11.75 %	4.71 %	12.05 %	19.16 %	10.21 %
Organic	36.88 (ignition loss)	9.40	8.50 (ignition loss)	8.32		6.17	6.25	8.61	6.80
N	(3.15 as NH ₃ and strong qual. reac- tion for uric acid)	0.56	—	—	—	0.34	—	0.72	—
CaO	22.41	39.92	42.34	42.74	40.93	43.01	42.34	34.69	41.40
MgO	1.46	6.97	2.75	2.54	0.74	2.32	0.71	7.26	1.23
Fe ₂ O ₃	tr.		tr.	tr.	—	—	0.14		0.54 (Fe)
Al ₂ O ₃	—		—	—	—	0.96	0.09		—
SO ₃	2.36		1.24	1.30	5.66	—	1.19		2.43
CO ₂	—		3.21	2.48	—	0.27	2.99		4.60
Alkalis, chlorides, etc.	4.44		—	—	—	2.33	1.78		0.56 (NaCl)
P ₂ O ₅	21.27	35.81	40.14	39.70	40.47	39.44	32.32	29.55	32.23
SiO ₂ , insol.	0.78	0.60	—	—	—	0.79	0.14	0.73	—

inch thick. These strata presumably marked old surfaces which Hague thinks had been occasionally flooded by high seas breaking over the rim. It is possible that cargoes containing much crust, recorded as received in Germany by Heiden (1887), came from such parts of the deposit.

A number of analyses of Baker Island guano have been published and are presented in table 15.

Baker Island was worked by the American Guano Company from 1859 to 1878 (Bryan, 1942). The "Report to stockholders" (American Guano Company, 1857) indicates that the deposit on Baker Island was expected to exceed the 7,000,000 tons estimated to be present on Jarvis Island. This expectation was

1872, to November, 1872, 11,148 tons were removed in eight vessels (Hempstead, 1873; *The Friend*, April, 1873, p. 29), though Commander Richard W. Meade reported 20,000 tons piled up for loading in the spring of that year (United States Hydrographic Office, 1873). The record for 1873, which may be incomplete, indicates 5885 tons removed in four vessels, and thereafter the trade evidently declined, as further reports are not given.

It seems likely that for the whole period of

¹ The last vessel, the "Centurion," evidently left abnormally late and probably had difficulty in loading. Normally no loading was done in the early months of the year. The "Centurion" carried only 500 tons of guano, so the order of magnitude of the output for 1869 is unaffected by omission or inclusion of this vessel.

exploitation the total output cannot have exceeded 12,000 tons per annum, even though Meade's observations suggest that the whole of the guano that had been dug could not always be shipped during the season when vessels safely lay at the moorings. If the upper estimate of 12,000 tons per year be accepted, the total amount of phosphate shipped from Baker Island cannot have exceeded 240,000 tons. Digging was continued by John T. Arundel and Company from 1886 to 1891 (Bryan, 1942). Six years more at the maximum rate, certainly an exaggeration for this period, would add 72,000 tons. An original reserve of the order of 250,000 to 300,000 tons is therefore a reasonable estimate.

JARVIS ISLAND

LATITUDE 00° 23' 33" S., LONGITUDE 160° 03' W.

Described by Hague; has the remains of a central lagoon, but this is now normally dry. The island is about 1.6 by 3.2 kilometers and has an area of about 4 km². The maximum elevation of the rim is given as 3.0 to 3.7 meters by the "Pacific islands pilot" (United States Hydrographic Office, 1926) above sea level. Wentworth and Palmer (1925), however, say that the greatest height is 7.5 meters, but that there is no reef rock above about 4 meters (12 feet), the higher parts of the island being built of detrital material cast up by the waves. Whereas on Baker Island or Howland Island, shafts dug in the central depression encounter hard coral below the guano, on Jarvis Island the lagoon appears to have filled with coral sand and shells. The filled lagoon floor now stands 2.0 to 2.5 meters (7 to 8 feet) above sea level. Towards the end of the filling process the lagoon waters evaporated, depositing gypsum over a large part of the floor, the more soluble salts washing away into the remains of the lagoon. Concentric beach lines indicate former positions of the lagoon margin. This process apparently continued until after the main guano deposit had formed, but it is not clear from Hague's account whether or not the last deposit of gypsum, mixed with sodium chloride and other salts, round the final remains of the lagoon is stratigraphically continuous with the main gypsum hard-pan under the work-

able guano deposit. A more recent investigation by Christophersen, discussed below, suggests at least two periods of guano deposition with CaSO₄ formation between them.

Hague says that the vegetation of the interior, consisting of long coarse grass (presumably *Lepturus repens*), "mesembreanthemum" (? = *Sesuvium*), and "Portulaca," was mainly confined to the outer part of the interior where the substrate consisted of guano mixed with coral sand. At present the vegetation of the central depression consists of scattered *Sesuvium portulacastrum* Linnaeus, *Boerhaavia tetrandra*, *Sida fallax* Walpers, *Lepturus repens* (Forster) R. Brown, which is exceptionally abundant in the sooty tern colony on the northeast part of the island, *Portulaca lutea*, and *Tribulus cistoides* Linnaeus (Christophersen, 1927).

Very considerable amounts of phosphate have been exploited. The material lay in part on coral rocks, in part mixed with coral mud, and in part deposited on the extensive bed of gypsum formed by evaporation. Hague's analysis of the dark brown powder found over coral rock is as follows:

H ₂ O at 100°C.	5.02%
Ignition loss	8.45
CaO	42.17
MgO	1.02
SO ₃	3.06
P ₂ O ₅	34.01
CO ₂	0.81
Insol. residue	0.60
Indet.	4.86

If the sulphate be all present as gypsum, and the carbonate as CaCO₃, the corrected CaO becomes 39.00%, giving a molecular ratio CaO:P₂O₅=1:0.343. Some of the magnesium was no doubt also present as phosphate. The phosphate deposit that overlay the gypsum was of a different character. The surface consisted of a crust, below which there might be up to a foot of phosphate more or less mixed with sulphate.

The crust consisted, at its purest, of:

H ₂ O at 100°C.	0.12%
Combined water with organic matter	9.62
CaO	38.32
SO ₃	1.63
P ₂ O ₅	50.04
Undet.	0.27

Allowing for the sulphate as gypsum, there remains combined water and organic matter 8.89%, CaO 37.18%, P_2O_5 50.04%; the molecular ratio $CaO:P_2O_5=1:0.53$. The main constituent of the crust was presumably the anhydrous $CaHPO_4$, monetite, which ideally contains P_2O_5 52.2%, CaO 41.2%, H_2O 6.6%. In many places the crust was peculiar in the presence of bubble-like structures up to 7 inches high and 10 inches wide. They consisted of a pure outer layer of phosphate and a pure inner core of soft powdery gypsum. The intermediate layers contained both sulphate and phosphate. These structures occurred mainly where the underlying material was dark colored and damp, consisting of a mixture of calcium sulphate and phosphate, with presumably some organic matter. Hague supposes that they formed over bubbles of CO_2 , generated below the crust while the latter was fresh and plastic. Analyses by Johnston (Webb and Sardy, 1859) and Liebig (1860) indicate that the material rich in sulphate, presumably from below the crust, contained $CaHPO_4$ as well as more basic phosphates. Allowing for $CaSO_4$, Liebig gives 17.40% $Ca_3P_2O_8$ and 16.03% $CaHPO_4$. Hague believed that the genesis of the monohydrogen phosphate was due to the presence of sulphuric acid set free by the decomposition of the gypsum; what happened to the excess calcium of the gypsum is not indicated. The most reasonable explanation of such a crust of $CaHPO_4$ on the surface of the deposit is the upward capillary movement of a solution enriched in phosphate owing to incongruent solubility of the original material.

All the commercial analyses contained considerable amounts of sulphate; Drysdale (1861) gave the mean of 100 analyses as 4.74% gypsum and 74.89% alkaline earth phosphates. The more detailed analyses (I) of Liebig (1860), (II) of Voelcker (1876), and (III) of Heiden (1887) are clearly derived from material mixed with much more gypsum (see table at head of column 2).

Several other less complete analyses of no individual interest are given by Heiden, who concludes that the mean P_2O_5 content was 20.66%. In view of Drysdale's analyses the latter value is clearly too low.

The profile in the center of Jarvis Island

	I	II	III
Water	12.118%	11.27%	15.834%
Organic	5.992	9.93	9.409
N	0.647 ^a	—	0.321
Fe_2O_3	0.090	—	0.034
CaO	34.839	37.18	33.512
MgO	0.568	12.63	0.034
K_2O	0.456		0.0675
Na_2O	0.332		
SO_3	27.021		21.741
P_2O_5	17.676	23.88	18.146
Cl	0.203	—	0.214
Sand	0.273	0.09	0.400 ^b

^a NO_3 0.313%, NH_3 0.039%.

^b +0.612% sol. silicate.

has been studied more recently, in 1924, by Christophersen (1927) who examined trenches dug by guano workers. The stratigraphy exhibited was found to be more complex than would be expected from Hague's account.

	CENTI-METERS
I. Light brown mealy sand with root fibers, rich in phosphate and calcium (layer probably formed during disturbance by guano diggers)	10
II. Hard pan, mainly gypsum. Phosphate reaction marked, but less than in I	13-21
III. White to brown sand, probably unconsolidated gypsum, rich in magnesium; phosphate present, but less than in other layers	41-47
IV. Crystalline layer	} Phosphate beds 11-15
V. Hard brown layer	
VI. White hard pan, phosphatized coral sand	40-50
VII. Phosphate bed, like V	18+
VIII. Coral limestone uncovered in a few excavations	

If, as Christophersen supposes, the top layer represents material disturbed in removing guano over the gypsum hard-pan, it is clear that there must have been at least two periods of guano deposition, separated by a rise and fall of the lagoon level. If a superficial layer of guano has been removed, and IV to V and VII represent old guano deposits, there must have been three periods of bird colonization, the first two separated by distribution of coral sand (VI) by wind or

water, the second and third by formation of the gypsum layer.

Bryan (1942) states that guano exploitation began on Jarvis Island in 1858 and continued until 1879. The island was claimed by the American Guano Company, which alleged in their "Report to stockholders" (American Guano Company, 1857) that 7,000,000 tons of phosphatic guano existed on the island. In view of the known length of the period of exploitation it is certain that this estimate was a gross exaggeration, but as Christophersen's profile evidently indicates phosphate that was left by the guano diggers at some depth below the original surface of the island, it is not unlikely that the amount of P_2O_5 per unit area was originally greater on Jarvis Island than on Baker or Howland Islands. Hague, who knew the islands personally, notes in reminiscences published in 1902 that a prospectus issued in 1897 by a British Company indicated 120,000 tons of phosphate left on Jarvis and Baker Islands together. Since Hague does not express incredulity and since the prospectus was presumably issued by J. T. Arundel, who had a very fine reputation in the Pacific, the estimate, though probably rather optimistic, was presumably based on some valid information. Bryan, however, indicates that the Pacific Phosphate Company did not lease the island until 1906, and that little digging was done. The 21 years' digging by the American Guano Company might have removed from Jarvis Island 200,000 or 300,000 tons. An estimate of the kind made in 1897 of the remaining reserve would not be unreasonable in view of the fact that some phosphatic material still exists on the island.

MALDEN ISLAND

LATITUDE $4^{\circ} 03' S.$, LONGITUDE $154^{\circ} 59' W.$

A roughly triangular atoll having an area of 78.8 km^2 , of which 36.1 km^2 are occupied by a lagoon set to the east of the center. There is a fringing reef about 60 meters wide within which the rim of the island rises (fig. 49). Dixon (1878a, 1878b), the most important authority on the island, noted nine ridges of broken coral on the north and south sides, and observed such a ridge being formed by large rollers coming in over the reef. The

height of the top of the beach varies from 2.7 to 6.4 meters. ("Pacific islands pilot," 1926, gives up to 9.1 meters.) Within the bank, the land slopes gradually to the interior of the plain of the island, with the lagoon on the east side. This interior plain lies about 1 meter above the water level. Dixon concluded that elevation of about this amount had occurred. Ball (*in* Emory, 1934) found no raised beach, but concluded from the finding of old coral heads *in situ*, "a few inches above the level of the water in the lagoon," that some emergence had occurred.

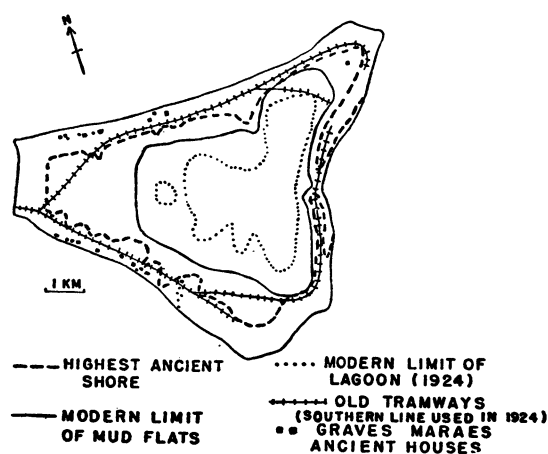


FIG. 49. Map of Malden Island. After Bryan.

The lagoon lacks an open channel to the sea but is connected through fissures as its water rises and falls with the tide. Evaporation in the lagoon causes a continued influx of sea water and deposition of salts in the shallow water and adjacent margin of the bank. After occasional rainstorms, the lagoon and the salt deposits on the shore are washed out with fresh water, the more soluble components are removed, and calcium sulphate, with some carbonate, is left to cover large tracts a few inches above water level. The surface of the calcium sulphate deposit forms a crust, the soft material being apparently bound together by an alga. Pieces of the crust may be detached during violent winds and carried westward to form a slope towards the center of the island where the material is colonized by a mesembryanthemum-like plant. This plant catches dust blown up, forming a ridge about half a

meter high, in which mutton birds burrow, delivering organic matter and phosphate to the soil. Ten species of plant were noted by Dixon but not identified. The low ground near several subsidiary lagoons was covered with the "mesembreanthemum" (? *Sesuvium*), the bank of the island by "Portulaca," and kupatea trees are said to occur.

Traces of former human occupation exist, and the inhabitants of Manihiki are said to have traditions of chiefs and of a population washed off the island; Dixon regards this as improbable. Malden Island, however, is remarkable for its archaeological remains, the best account of which is that by Emory (1934). The ruins consist of stone enclosures and platforms. Emory thinks that some represent maraes, or shrines; others perhaps house sites and tombs. The more elaborate structures are most like maraes on Raivavae, in the Austral Islands. One shrine on Raivavae which is comparable to the Malden structures, though more elaborate, is known to be late eighteenth century. It is therefore not improbable that the Malden structures are relatively recent, though the disposition of the paved paths that are associated with some of the structures indicates that they antedate the formation of the last three coral ridges. None of the ruins is guano covered; they probably do not stand within the area of recent bird colonies. Emory thinks, however, that some are situated above the top layer of guano.

Dixon states that 14 species of birds inhabit the island, the most numerous being the black wideawake (*Sterna fuscata oahuensis*) and the frigate bird (*Fregata* sp.). The tern colony occupied five acres of ground when Dixon arrived in 1866 but was subsequently much reduced by the depredation of feral cats. The birds nested under the shelter of *Portulaca* plants, and there was approximately one egg laid per square foot. A single egg is laid, but another can be produced if the first is removed without too much disturbance. Nesting occurred twice a year, in October and April. The frigate bird, a well-known marauder and thief, pestering other sea birds, formed a colony breeding on level ground, where the *Portulaca* is short. The extent of the colony seems to have been about 2 acres; breeding took place in De-

cember and June. The total colonies of these species thus seem to have occupied about 7 acres; if three more be allowed for the rarer species, only about 0.1% of the dry surface of the island can have been occupied by breeding birds. Bryan (1942) says that except for *S. f. oahuensis* all sea birds had become rare by 1924.

The guano deposits, according to Dixon, were found either in the region occupied by birds or in crevices and pockets among the rocks. The newer deposits are very rich in phosphates. Older and more widespread deposits are of poorer quality; much was not worth removing. They were supposed by Dixon to have been "washed by water or blown by the wind, or possibly there deposited anterior to the occupation of the island by natives." This last interpretation is plausible.

Dixon's analyses of supposedly recent guano are admittedly rough, and the calcium carbonate and sulphate may well be wind-blown material.

	<i>Sterna</i> (MEAN OF Two)	<i>Fregata</i> (MEAN OF Two)	<i>Puffinus</i> (MEAN OF THREE)
Water and organic matter	12.26%	10.58%	24.74%
"Calcium phosphate"	75.85	83.13	50.33
CaCO ₃	6.76	5.07	n.d.
CaSO ₄	4.00	0.89	n.d.
MgCO ₃ , alkalis, sand, loss	1.13	0.33	0.21

The organic matter is mostly roots of plants, very low in nitrogen. The mutton bird guano is greatly contaminated by the burrowing habits of these birds. Dixon notes that three months after the birds leave the breeding grounds the ammoniacal odor, which is pronounced when the breeding area is occupied, disappears; this happened even when no rain fell. The more recent guanos that he analyzed presumably had been deposited long enough prior to analysis for the loss of nitrogen, implied by these observations, to have taken place. Such loss is attributed by Dixon to rapid decomposition in deposits heated by the sun. As has been indicated above, temperatures up to 57.2° C. are recorded immediately below the soil surface. It is possible that rapid decomposition

by thermophilic bacteria plays a great part in diagenesis, and that on the sites occupied on the Peruvian coast, the guano dries quickly enough to retain its nitrogen, while on the Pacific islands, with possibly higher ground-temperatures and a more humid atmosphere, the drying is delayed long enough for decomposition to take place.

The old guano deposits of Malden Island occur within the encircling ridge on flat ground about a meter above water level. The surface is level, but below it projecting pieces of coral rock enclose pockets of phosphate. The surface layer is always contaminated with CaCO_3 . This material, being wind borne, or occasionally perhaps water borne, is from its superficial occurrence apparently more easily disturbed today than formerly; this suggests an initially larger bird colony. The deeper layers, when above water level, are soft and yellowish brown when dry; dark chocolate grains ("shotty phosphate") mixed with minute white specks occur below water level. The bottoms of the shallow pockets that did not extend to water level were lined with an indurated guano evidently corresponding to the crust guano of Voelcker and containing:

Water	2.60%
Organic matter and combined water	6.45
P_2O_5	43.04
SO_3	0.62
CO_2	tr.
CaO	43.45
MgO	3.97
$(\text{Al}, \text{Fe})_2\text{O}_3$	tr.

Such crusts, above water, were supposed by Dixon normally to contain magnesium phosphate. In the deeper pockets, a brown crust of phosphate is found on the rocks at the sides of the pockets. It begins as a thin glaze, but at water level or below is up to 15 cm. thick. It is principally calcium phosphate, free from magnesium. Minute white specks, presumably of unaltered CaCO_3 and effervescing with acid, occur throughout the crust. Beneath the crust the coral rock is very decomposed and soft. Analyses of two sets of samples collected in commercially valuable parts of the field give mean values:

	IGNITION Loss	$\text{Ca}_3\text{P}_2\text{O}_8$	$\text{Ca}_3\text{P}_2\text{O}_8$ IN ASH
0-6 in.	23.91%	31.46%	41.3%
6 in.-water level	21.52	58.73	74.1
Shotty phosphate to 18 in. below water level	24.16	72.19	95.1
Encrusting phosphate	7.28	87.82	93.6

While the reference of the calcium phosphate to $\text{Ca}_3\text{P}_2\text{O}_8$ is obviously arbitrary, it is certain that below water level a relatively pure phosphate rock is formed, probably by replacement of the calcium carbonate. Replacement by phosphate of the CaCO_3 of fragments of coral rock at the surface of the guano was also noted. Dixon attempted to imitate the process artificially but without success.

Malden Island was claimed by the United States Guano Company, but they do not appear to have worked the island, possibly because they found British phosphate diggers already in operation, for Bryan (1942) says exploitation had begun by 1856. In the United States Guano Company's (1859) "Report to the stockholders," it is said that guano was discovered in May, 1842, by Captain Netcher, and an estimate of more than 5,000,000 tons reserve is given.

According to Heiden (1887) on the authority of Herr Emil Güssefeld, who was concerned with the import of Malden guano, the annual export from the island was, during the 1880's "Ca 8-100000" tons. This figure seems to be greatly exaggerated. The total import to Hamburg from Malden during the period from the beginning of 1871 to September 30, 1883, was 64,631 tons, while from Baker Island during the period 1871 to 1879 it was 43,489 tons. The figures for individual years, though very variable, are of the same order of magnitude; the Baker supply, however, became exhausted in 1879. In 1872 the Baker cargoes brought to Hamburg amounted to 8648 tons, while from the report in *The Friend*, as indicated above, the total export from Baker was 11,148 tons. These figures suggest that Hamburg received a large proportion of the material exported from the central Pacific islands. The known imports from Malden therefore seem con-

sistent with a yearly yield of the order of 10,000 rather than 100,000 tons.

Since Malden was not ever worked as an American island, the imports of guano from the island, if any were made, would, following the practice after 1869, presumably be listed in the "Annual reports of the commerce and navigation of the United States" (United States Bureau of Statistics), as foreign imports from the Pacific islands. Since no such imports are in fact listed, and since Malden Island also is absent from the tables giving imports from the supposedly American islands, there can be little doubt that no important quantity was brought to the United States. Some may have found its way to New Zealand and to other non-European markets, but it seems virtually certain that during the 1870's and 1880's most of what did not go to Hamburg was brought to British ports. The British statistics unfortunately do not distinguish the different Pacific sources, but from the whole Pacific area from the beginning of 1862 when Pacific island guano appears in the Trade and Navigation statistics (Great Britain, Parliamentary Sessional Papers, Trade and Navigation) to the end of 1886, the last year for an entry, 120,004 tons were imported from the area as a whole. If possible imports into Britain and to Hamburg are considered together, Güssfeldt's statement is seen to be entirely inconsistent with the available statistics. Moreover if the Malden deposits had produced 100,000 tons per year, the shipping to that island would have been of so much greater importance than to any other Pacific island that it is virtually certain that the island would figure far more conspicuously in accounts of Oceania than is actually the case. It is reasonable to assume that Güssfeldt actually meant 8000 to 10,000 tons. If the mean yield for the 70 years during which the island was worked be taken at about half the supposed maximum yield, the total amount exported would be 350,000 tons. The British Phosphate Commissioners state (*in litt.*) that in 1943 there were an estimated 100,000 tons left of material containing 40% to 50% phosphate. The original reserve therefore may reasonably be set at about 400,000 tons. This value is admittedly uncertain, being based on an emendation of Güssfeldt's figure and a specu-

lative guess as to the mean yield. It is, however, the best estimate now possible. In view of the large area of the island, such a reserve, though greater than that on the other islands, does not imply a greater depth of phosphatic guano.

It is easy to understand how the development of the phosphate industry at Ocean Island and Nauru led to abandonment of Malden prior to its exhaustion. Though Nauru alone will doubtless serve the requirements of Australia and New Zealand for the rest of the present century, it would be far-sighted policy to encourage the bird colonies on Malden and reduce as far as possible the rats and other predators, so permitting a new reserve to be built up on an island that seems to have few non-ornithological attractions.

THE PHOENIX GROUP

The group consists of the following slightly elevated atolls, arranged here from north to south:

- Canton (latitude 2° 49' S., longitude 171° 39' W., maximum elevation 6.1 meters)
- Enderbury (latitude 3° 07' S., longitude 171° 02½' W., maximum elevation 7.6 meters)
- Birnie (latitude 3° 35' S., longitude 171° 31' W., maximum elevation 1.8 meters)
- McKean (latitude 3° 37' S., longitude 174° 07' W., maximum elevation 4.6 meters)
- Phoenix (latitude 3° 42½' S., longitude 170° 41½' W., maximum elevation 5.5 meters)
- Sydney (latitude 4° 27½' S., longitude 171° 14' W., maximum elevation 6.1 meters)
- Hull (latitude 4° 30' S., longitude 172° 13' W., maximum elevation ?)
- Gardner (latitude 4° 37' S., longitude 174° 39' W., maximum elevation ?)

The diverse environments furnished by the different Phoenix Islands give considerable insight into the conditions necessary for production of a large deposit of phosphatic guano.

The climate of the Phoenix Islands is in general arid, as has been indicated above. There is, however, clearly an increase in precipitation in passing from northeast to southwest. Sydney, Hull, and Gardner have wild trees, mainly *Tournefortia*, *Pisonia*, and *Cordia*; coconuts can be grown quite well on these islands. The other islands have a very poorly developed scrub, and coconuts can be

grown with difficulty, if at all. Thus *Tournefortia* and *Cordia* both grow on Enderbury, where coconuts can barely exist. The same three trees can just grow on Canton. No trees exist on Phoenix, Birnie, or McKean Islands. The minimum rainfall therefore appears to be at about latitude $3^{\circ} 36' S$. The increase in rainfall is not geographically regular, for Hull is apparently not so wet as Sydney (Bryan, 1942). Gardner, Hull, and Canton have open lagoons with relatively narrow land rims. The other islands have closed or vanishing lagoons, now much modified by guano digging, and relatively broad land rims. Ruins of structures suggesting visitors from eastern Polynesia and from Micronesia have been found on Sydney and Hull Islands.

Gardner Island is not known to have yielded any phosphatic guano, though claimed under the Guano Act. Hull Island was not claimed. Bryan thinks that this was due to an error, the island being regarded as the same as Sydney Island. The only indication of guano on Hull that has been found is a statement in a brief article by Dickson (1939) that a "group of Americans visited Hull Island in March 1924. They found the American Shafer there in charge of a gang of Tokelan and Ellice Islanders collecting guano." The article further quotes from a press account (Honolulu Advertiser, July 10, 1937) of the search for Amelia Earhart in 1937, which refers to the "manager of the Guano Works on the island" and to the "thousands of birds, which were disturbed by the planes" and "formed a hazard to landing by the island."

Canton Island was claimed under the Guano Act, but Bryan indicates that it was apparently not worked until taken over by the British firm of John T. Arundel and Company, who dug a little guano in 1885 and 1886. An analysis given below has been published, but nothing else is known of the occurrence. It is thus clear that the three Phoenix Islands with narrow land rims contained relatively little phosphatic material and were not considered worth exploitation during the great days of the Pacific guano trade.

The other islands, in which the closed and partly dried lagoon provided a collecting basin for guano, were in general much more

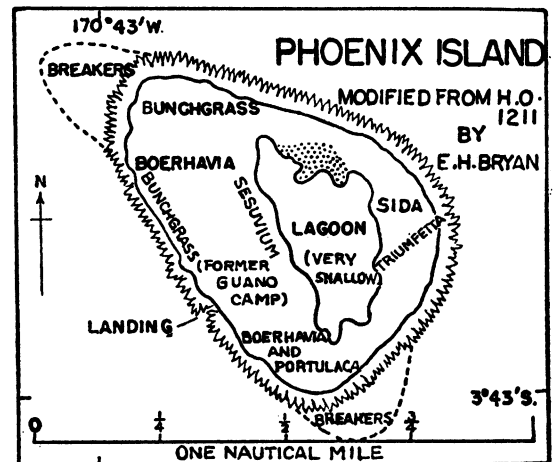


FIG. 50. Map of Phoenix Island. After Bryan.

important. Birnie Island, however, is an exception. Though claimed as a guano island under the Act of 1856, Bryan states that there is no evidence that any considerable amount of guano was dug. Hague merely indicates that it was reputed to have a deposit. Ellis (1937) implies that J. T. Arundel did not work the island, though he certainly visited it (Arundel, 1890). Though small, about 1200 by 550 meters, Birnie evidently has a well-marked rampart and a flat interior with a very small, shallow lagoon divided in two, and would seem to be a favorable site for accumulation of guano. The lagoon is not marked on the United States Hydrographic Office chart 125, based on the United States Exploring Expedition's survey, and seems to have been formed by the accretion of bars of debris between 1840 and 1883. The apparent poverty of Birnie, in contrast to the richness of the other closed Phoenix atolls, is curious, and no obvious explanation can be derived from the literature, except for Arundel's (1890) statement that the island had grown greatly between the United States Exploring Expedition's visit in 1840 and his own visit in 1883. If this is correct it may indicate great instability.

Sydney Island is a triangular island of maximum diameter just over 3 kilometers with a land rim in general about 500 meters wide and a very saline, closed, central lagoon. As far as can be judged from the disposition of the remains of the tramway, the guano deposits mainly lay along the northern and

eastern shores of the lagoon. They were clearly not very extensive, for, although the island was claimed under the Guano Act, Bryan (1942) found no indication that it was worked until 1882 or 1883 by John T. Arundel and Company who continued operations until 1884–1885. An analysis has been published and is given in table 16.

Phoenix Island is a pear-shaped island about 1.2 kilometers long (fig. 50). The lagoon occupies less than half of the interior, and from Bryan's account is probably of variable extent. The vegetation is composed mainly of *Lepturus*, *Boerhaavia*, *Portulaca*, *Sesuvium*, and *Sida* in different tracts over the island. The British Admiralty chart indicates a tramway from the landing on the west side towards the lagoon. The main guano deposit must have occurred along the central part of the island, and the lagoon is apparently largely due to removal of guano (Arundel, 1890). The exploitation of this guano was begun in 1860 by C. A. Williams and Company, later the Phoenix Guano Company, and was continued until August, 1871 (Bryan, 1942). An analysis has been published by Ullmann.

McKean Island is a small, roughly circular island with a maximum diameter of about 550 meters. (fig. 51). A curious walled depres-

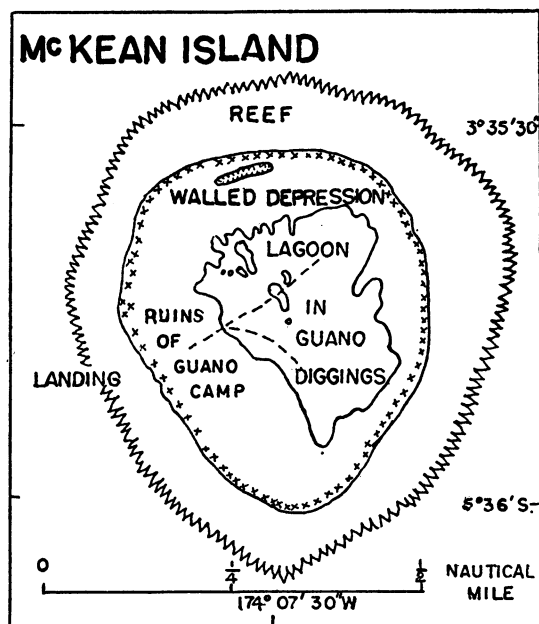


FIG. 51. Map of McKean Island. After Bryan.

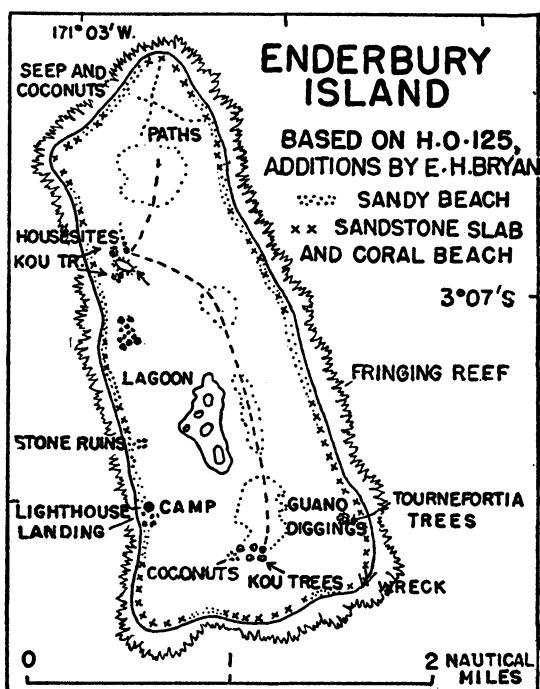


FIG. 52. Map of Enderbury Island. After Bryan.

sion exists on the northern side of the island. The lagoon now occupies a great part of the central plain, but in its present condition is largely the result of guano digging (Arundel, 1890). The exploitation of McKean Island by C. A. Williams and Company was begun in 1859, and by 1870 the locality was exhausted. During this period 30 cargoes were shipped (Phoenix Guano Company, 1871) corresponding presumably to between 20,000 and 40,000 tons. An island named Arthurs Island (latitude 3° 32' S., longitude 176° 05' W.), regarded by Bryan (1942) and by Dr. S. W. Boggs as identical with McKean, was claimed by the United States Guano Company. This concern stated in their "Report to the stockholders" (1859) that Capt. George S. Netcher discovered guano on it in 1842, and estimated an amount similar to that on Howland Island. The estimate of 2,867,646 tons given for Howland Island is certainly many times too great so that these vague remarks about Arthurs Island give little information about the McKean Island deposit. An analysis of McKean Island guano by S. W. Johnson, the well-known agricultural chemist, was published in a trade pamphlet (Phoenix Guano

Company, 1860). Other less informative but similar analyses from later cargoes, which do not all necessarily come from McKean Island, are given in a later edition (Phoenix Guano Company, 1871). Hague (1862) reports that much gypsum was present, though the analyses do not show an excessive amount of sulphate.

Enderbury Island was, with McKean Island, the most important source of guano in the Phoenix group. It is larger than the other closed islands, being rectangular, rather under 5 kilometers long, and about one-third that width (fig. 52). There is a small lagoon just south of the center of the island. Bryan's map indicates the principal diggings at the north and south ends of the island and along the sides of the lagoon. Schuch (1878) indicates that the deposit was about 30 cm. thick, while Voelcker states that both powdery guano and stony crust occurred.

Exploitation of Enderbury Island started in 1860, but the peak in production did not occur until 1870, in which year Bryan notes that four ships loaded over 6000 tons in 64 working days, while in 1872 three vessels loaded 4822 tons in 33 working days. The last guano was shipped in 1877 (Bryan, 1942). From 1871 to 1877 the quantity of phosphatic guano from Enderbury received in

Hamburg was 25,075 tons (Heiden, 1887). The imports in 1872 were 1800 tons, or rather over one-third of the total loading at the island. The total received in Hamburg therefore suggests that, if allowance is made for exploitation prior to 1870, the original deposit was of the order of magnitude of 100,000 tons. Analyses by Voelcker of both powdery and crust guano have been published and are given in table 16.

The molecular ratios $\text{CaO}:\text{P}_2\text{O}_5$, corrected for CaCO_3 , are 1:0.358 for the Enderbury powder and 1:0.372 for the first crust. Both analyses seem to imply the presence of a little phosphate less basic than $\text{Ca}_3\text{P}_2\text{O}_8$ or hydroxylapatite, but some magnesium phosphate may have been present.

STARBUCK ISLAND

LATITUDE $5^\circ 37' \text{ S.}$, LONGITUDE $155^\circ 53' \text{ W.}$

A slightly elevated atoll of maximum altitude 4.8 meters (United States Hydrographic Office, 1926), and, like Jarvis Island, containing a deposit of gypsum (Hague, 1862). There is a lagoon communicating with the ocean by a tunnel (S. C. Ball, *in litt.*). The United States Hydrographic Office chart 1980, also reproduced by Bryan (1942), indicates salt lagoons at the east end and guano

TABLE 16

	Canton Island (Grimm <i>in</i> Ullmann, 1906)	Enderbury Island (Voelcker, 1876)			McKean Island (S. W. Johnson <i>in</i> Phoenix Guano Co., 1860)	Phoenix Island (Ullmann, 1906)	Sydney Island (Gilbert, 1884)
		Powder	Crust	Crust			
H_2O	5.63%	8.76%	8.33%	11.67%	20.88%	4.93%	7.38%
Organic matter	—	8.81	6.45		8.07	8.66	7.29
N	0.54	0.38	—	—	—	0.63	0.28
$(\text{Al,Fe})_2\text{O}_3$	0.23	—	—	—	—	0.23	—
CaO	44.40	40.76	41.96	42.83	37.70	44.91	42.96
MgO	—	5.58	3.95	6.65	1.98	—	2.03
Alkalis, etc.	—				5.96	—	0.76*
CO_2	—	7.26	1.46	—	—	—	2.64
SO_3	—	—	—	—	2.14	—	1.63
P_2O_5	29.26	28.74	37.79	38.67	23.28	36.10	34.41
F	—	—	—	—	—	—	0.40
Insol.	—	0.09	0.06	0.18	0.00	—	—

* Na_2O , 0.76; Cl, 0.87.

diggings in the center of the island. Arundel (1890) mentions salt crystals in the lagoon and ridge after ridge of old block coral enclosing guano beds in the central part of the island. Arundel comments on the presence of sea birds, but Dr. Ball noted very few birds in December, 1924, when the Tanager Expedition visited the island. Arundel indicates that wideawakes occupied the western end of the island, while "further up," i.e., to the east, frigate birds, boobies, tropic birds, and mutton birds had colonies. The frigate birds occupied an area close to the booby colony, which they molested in the well-known manner. There seem to be no details available of the guano deposit, save Voelcker's (1876) statement that the guano often rested on, or was mixed with, a crust, free of contaminants, and frequently containing CaHPO_4 . The same author gives three analyses, two of which refer to crust:

	POWDER	CRUST 1	CRUST 2
H ₂ O	11.56%	} 8.75%	} 10.01%
Organic	7.25		
N	0.39	—	—
CaO	41.04	40.94	44.96
P ₂ O ₅	33.61	45.57	40.12
MgO	1.16	0.64	} 4.87
SO ₃	0.88	3.56	
CO ₂	1.05	—	
Alkalis	3.43	0.47	
SiO ₂	0.02	0.07	0.04

The molecular $\text{CaO}:\text{P}_2\text{O}_5$ ratio, corrected for CO_2 and SO_3 , is 1:0.337 for the powder and 1:0.48 for the first crust, in which monite was doubtless present. Voelcker's statement that the crust lay under the powder is possibly erroneous. It seems more likely that the crust was comparable to that at Baker and Jarvis Islands. The occurrence at Malden gave unequivocal evidence of enrichment of phosphate with depth, but there is no reason why enriched solutions should not deposit phosphate both below and above the guano layer.

Exploitation began shortly after 1866 and continued till after 1874. In 1872 about a hundred Kanakas worked on the island (Bryan, 1942, from account by George Thompson). This is a rather large number of laborers so that it is reasonable to suppose that the original deposit contained tens of thousands of tons. In the three years from

1871 to 1873, 5925 tons were received at the port of Hamburg (Heiden, 1887) but none in subsequent years.

CORAL ISLAND

LATITUDE 7° 53' S., LONGITUDE 140° 24' W.

The Cotar Island of the "Pacific islands pilot," also known as Ile à Fleur d'Eau and Ile de Sable, the most northern islet of the Marquesas group. Chubb (1930) thinks it is probably not a true atoll but merely a sand or ash bank. It is said to disappear after gales (Chubb, 1930). It is possibly the source of a sample analyzed and published as from Coral Island by Voelcker (1876). The islet is described as but 1.8 to 2.7 meters above sea level, and not over 150 feet long. Voelcker found:

H ₂ O	7.04%
Organic matter	11.76
Nitrogen	0.38
CaO	41.76
MgO, alkalis	
(SO ₃ , CO ₂ , etc.)	3.55
P ₂ O ₅	35.29
Insol.	0.60

HERGEST ROCKS

LATITUDE 8° 41' S., LONGITUDE 140° 37' W.

Three rocks, of which the largest, a volcanic peak 220 meters high called Motu Iti, has a little vegetation, while the two lower ones are white with guano ("Pacific islands pilot," vol. 2). This deposit was discovered prior to 1855 (Great Britain, Parliamentary Sessional Papers, 1854-1855), when G. C. Miller, British Consul at Tahiti, wrote that guano existed on the smaller of two islets called Hergest's Rocks near Nukahiva. An agreement for exploitation was made by the firm of Rankin, Gillmore and Company of Liverpool with the French government, and a Mr. Lamont who had experience with the Ichabo trade investigated the deposit, which had been known only on the strength of vague and ancient accounts. He was unable to land owing to the declivity of the rock and the heavy sea at the time of his visit. He estimated that the rock examined bore 4000 to 5000 tons of phosphatic guano. The locality is recorded as phosphatized by Privat-Deschanel (1910), but nothing more is known of it. It is of interest to note that Miller con-

sidered sea birds as common in the Marquesas, but very scarce in the Tuamotu Archipelago and at Tahiti, where guano was unknown.

AN INTERMEDIATE, ALMOST UNPHOSPHATIZED ISLAND

CHRISTMAS ISLAND

LATITUDE 1° 55' N., LONGITUDE 157° 20' W.

A very large atoll, with a large eccentric lagoon and other closed salt lakes. The maximum elevation of the land surface is 12.2 meters. Elevated reef rocks imply emergence of 3 to 4 meters (Wentworth, 1931). The climate is intermediate between that of the wet islands discussed below and the dry islands, rich in guano, that have just been treated at length. The vegetation is similarly intermediate in character; planted coconuts flourish under cultivation, but there is little natural forest; such as exists is composed of open stands of *Tournefortia argentea* Linnaeus fil. with *Sida fallax*. Most of the natural vegetation constitutes various scrub associations, notably *Lepturus repens* and *Sida fallax* (Christophersen, 1927). Twenty-four species of vascular plants are, however, known from the island.

The former existence of any significant deposit of phosphatic guano on Christmas Island is very questionable. Cook (1785) who discovered the island in 1777 wrote, "The soil of this island, in some places, is light and black, evidently composed of decayed vegetables, the dung of birds and sand." He apparently indicates sooty terns in immense numbers breeding under bushes, and probably also *Sula s. rubripes* and *S. leucogaster plotus* as well as other birds. The existence of phosphatic soils is confirmed by Wentworth who states that "where groves of older trees have stood for some years, a considerable amount of phosphatic material derived from the excrement of sea birds is mingled with other soil elements." The presence of discrete phosphatic guano deposits is much more doubtful.

In 1825 Captain John Stetson, of New Haven, Connecticut, is said to have discovered guano deposits on the island. In view of the lack of interest in guano at that date, the discovery was probably made mentally and

in retrospect. Capt. Jason L. Pendleton took possession on June 20, 1858, on Stetson's behalf. Stetson disposed of his claim to A. G. Benson, whence it passed to the United States Guano Company. In the "Report to the stockholders," the company speaks of "its great deposits of Guano," but the support for this statement is merely an affidavit of J. P. Jayne who visited the island in 1834 and who mentions "two large hills, which deponent, when there, thought to be sand, but now believes to be piles of guano" and who also says that "the interior of the island, and in fact most of its surface, is covered with fish bones, bird dung and decayed animal matter." The first statement is obviously valueless; the second does not go much further than that of Captain Cook.

The only indication that guano digging took place is Bryan's (1942) remark that the United States Guano Company worked the island for several years after November, 1858. This statement can hardly be reconciled with the meager references to Christmas Island in the shipping intelligence published in *The Friend*. Hague (1862), who was associated with the rival¹ American Guano Company, moreover wrote that he had good reason to believe that no phosphate worthy of the name occurred on Christmas Island. A British license to work guano on Christmas Island was issued to W. L. Crowther in 1866 but was revoked in 1869, the island having proved unproductive (Crowther, 1939). In 1872 Meade found the Phoenix Guano Company in possession, but there is no evidence that any guano digging was being done. Elschner (1913) says that the phosphate of Christmas Island is highly impure; this statement may refer to phosphatic soil. Power (1925) states categorically that no exploitation of phosphate has ever taken place on the island.

Summarizing this evidence it seems clear that phosphatic soils occur but almost certain

¹ Though records of disputes between the companies exist (Bryan, 1942), the rivalry was probably apparent rather than real, or confined to the employees in the Pacific, for A. G. Benson was president of the American Guano Company and a trustee of the United States Guano Company, and a certain G. Hall a trustee or director of both companies. Commercial antagonism between such closely related companies can hardly have biased Hague's remarks in a scientific journal.

that no significant amount of relatively pure phosphatic guano has ever been discovered on the island.

WET ISLANDS TO THE NORTH

The three wetter Line Islands all appear to have had limited phosphatic deposits. On Washington Island the complete rampart and enclosed fresh-water lagoon insure that solid phosphatic material deposited within the atoll rim will remain on the island. On Fanning and Palmyra it seems certain that some of the phosphatization occurred under conditions very unlike those prevalent today.

FANNING ISLAND

LATITUDE 3° 51' N., LONGITUDE 159° 21' W.

The only one of the three wetter Line Islands from which commercially workable amounts of phosphate have been taken. The island is a large, irregular atoll with a fairly narrow, broken land rim and a very extensive lagoon partly drying at low tide. The area of the land surface is apparently about 33 km² (Bryan, 1942).

Most of the island is given over to the cultivation of coconuts (Herms, 1926; Christophersen, 1927), but *Pisonia* groves occur in various places, and Christophersen quotes from an unpublished manuscript of Merrill indicating that boobies nest in the branches of the trees in great numbers. It is possible the *Pisonia* groves occupy sites over phosphatized coral, as on Palmyra, but no observations were made on the soil profiles.

Keyle (1861) apparently gives the first indication of guano on Fanning Island, though the island had been bonded under more than one name by 1858. Keyle writes, "with regard to its soil, it is in some places sandy, in others it is of dark earthy mould intermixed with patches of phosphatic guano of fine quality." A report¹ submitted to the Secretary of the Navy by Commander J. S. Skerrett, U.S.S. "Portsmouth," and dated February 5, 1874, states that guano deposits were discovered by Mr. Greig and on analysis proved very rich. The most important of these deposits was a short distance from Whalers Anchorage, in the northwestern part of the island. The total quantity present was

estimated as 14,000 tons. Bryan notes that Hawaiian shipping records indicate that many vessels sailed to Fanning Island for guano in 1877-1879, and that some was shipped as late as 1885; after 1887 copra became the main export from the island. Heiden indicates that in 1878, 1275 tons of phosphatic guano reached Hamburg from Forming Island (*sic*), while in the three succeeding years no fewer than 20,250 tons were imported from Fanning Island. The first entry as well as the second presumably refers to Fanning Island, so that at least 21,525 tons must have been removed from the island. As it is unlikely that the whole of the Fanning Island material went to Germany, an estimate for the original reserve of 30,000 to 40,000 tons is reasonable. It is at any rate certain that the estimate reported by Commander Skerrett was too low.

The only adequate analysis available is by Gilbert (Stutzer, 1911), who found:

H ₂ O	8.00%
Organic	12.32
CaO	42.84
MgO	0.61
P ₂ O ₅	34.16
SO ₃	0.19
CO ₂	1.30
F	1.01

Keyle's account and the fact that the working of the deposits took place relatively late in the history of exploitation of the phosphatic guanos of the Line Islands suggest that the material was not exposed at the surface. The rather high fluorine content, if it be reliable, probably supports the contention that the Fanning Island phosphate did not represent contemporary deposition of guano. Elschner (1913) and the "Pacific islands pilot" (United States Hydrographic Office, 1916b) say that the deposit was of poor quality, but this is not confirmed by the analysis. It is apparent that, as well as the better grade, exported in the 1870's, partly phosphatized coral sand and phosphatic soils, formed under trees where birds nest, occur on Fanning Island. Elschner (1923) indeed gives four phosphate determinations, two of sandy phosphatic soil containing 15.0% P₂O₅ and 16.9% P₂O₅, and apparently two of so-called alluvial phosphatic soils containing 1.4% P₂O₅ and 25.0% P₂O₅.

¹ A transcript of this report was kindly made available by Mr. S. W. Boggs of the Department of State.

WASHINGTON ISLAND

LATITUDE 4° 43' N., LONGITUDE 160° 25' W.

A remarkable atoll about 6.1 kilometers long and 2.3 kilometers wide. The rim is complete and the lagoon, transformed into a fresh-water lake, is said to be about 9 meters deep (Wentworth, 1931). A large part of the lagoon at the western end of the island must formerly have been filled with water, but is now occupied by a peat deposit usually about 1 meter thick but in places reaching a depth of 1.6 meters. The atoll rim is surrounded by actively growing reefs up to 200 meters wide and covered with not more than 1 meter of water at low tide. The maximum elevation of the land appears to be about 6 meters (Wentworth, 1931), though the "Pacific islands pilot" gives but half that height. No elevated coral has been discovered *in situ* high enough to provide unequivocal evidence of emergence. Wentworth, however, notes sandstone and conglomerate, not of aeolian origin, and suggests that they were formed when the sea lay at a higher level than it does today. The general form of the island with its completely enclosed lagoon suggests such emergence.

The vegetation of the island is very well developed. *Tournefortia argentea* and *Lepturus repens* occupy the beach crest, the *Tournefortia* trees growing to a height of 8 to 10 meters. Within the crest a coconut forest with *Asplenium nidus* Linnaeus occupies most of the old land surface. A narrow belt of *Pandanus*, with *Polypodium scolopendrum* Burmann, represents a late stage in the invasion of the peat bog by forest, while a pure growth of *Cytosperma chamissonis* (Schott) Merrill represents the earlier phase of the invasion. The bog itself is formed by *Scirpus riparius* Presl. The vascular flora of the island comprises 35 species (Christophersen, 1927). In 1906 the remains of a canoe were found under 1.37 meters of peat in the bog that has replaced the western part of the lagoon. This canoe remained on the island from 1906 to 1917, when it was presented to the Bernice P. Bishop Museum. In its present state it bears nail marks and an augur hole. Emory (1934) regards these as having been made subsequent to discovery, though the evidence is not quite unequivocal. The typology of the

canoe raises difficult problems. It is not exactly paralleled by any known Polynesian craft. Emory, influenced by the affinity of the archaeological finds on Fanning Island to Tongan structures of the sixteenth century, suggests that the canoe is of medieval Tongan origin. The various islands have, however, been visited by many different groups of Polynesian navigators. Tuamotan affinities have already been indicated for the Howland excavations, Austral Islands affinities for the Malden remains. The presence of the snail *Pupoidopsis hawaiiensis* on Christmas Island indicates Hawaiian visits. The parrot *Vini kuhlii* on Washington itself suggests communication with the Austral Islands, but the bird may have been brought from Fanning Island. The canoe at least indicates that the development of the peat was a rapid and fairly recent event; the remaining part of the lake is apparently too deep to permit further reduction in area by encroachment of the bog (Christophersen, 1927).

Evidence of the occurrence of phosphatic guano on Washington Island is provided by the statement in the "Pacific islands pilot" that guano occurs but has not been exploited and by Power's (1925) enumeration of Washington Island as one of the islands that is too poor or too depleted to permit exploitation. More specific information is available from Elschner who appears to have visited Washington Island as a phosphate expert. He indicates (1915) that a clay-like calcium phosphatic mud probably acts as a seal, retaining the fresh water in the lagoon, and subsequently (1922) he regarded such material as a colloidal calcium phosphate with some organic matter, formed as a precipitate from the water of the lagoon into which guano is still being washed. If Elschner's belief as to the continuous contemporary origin of the material is correct Washington Island is the wettest island for which there is clear evidence of contemporary phosphatization. This is obviously owing to the existence of the completely closed lagoon. In a later paper (1923) Elschner gives a number of phosphate determinations showing stages in phosphatization of the coral sand and detritus; these appear to refer to material from Washington Island.

	P ₂ O ₅
Beginning of phosphatization, sand grains with a yellow shining surface of phosphate	2.42%
Intermediate stage, sandy	16.9
Almost complete	30.4
Phosphatized coral mud, so-called alluvial phosphate	34.1
Conglomerate, white internally	12.2
High grade phosphate, 15 cm. thick	35.4
From soil containing	9.7

Another analysis of a phosphate with the grains not completely cemented, so that interstitial spaces remained between them, gave 12% organic matter and 20% CaCO₃. This material is alleged to have contained the equivalent of 83.82% Ca₃P₂O₈, i.e., 38.4% P₂O₅, with little CaHPO₄, but clearly the figures given are erroneous. Elschner also examined a damp phosphate from under trees on which *Sula* sp. were breeding, near the lagoon. The interior of the individual particles of fragmental material is said to have contained 22.5% CaHPO₄, the cement 19.3% CaHPO₄, the outer layers of the detrital material are interpreted as Ca₃P₂O₈, and the whole mass contained 12.9% CaHPO₄. Elschner concludes from such material that in phosphatization, the coral sand is first phosphatized on the outside. As the process continues, the spaces between the fragments are more and more filled up with phosphate and the internal cores of CaCO₃ become smaller and smaller. In these stages there is little or no CaHPO₄. The diphosphate appears only when the interstices are almost filled and practically no carbonate is left. It is not clear from his account what method was used in reaching these conclusions.

PALMYRA ISLAND

LATITUDE 5° 23' N., LONGITUDE 162° 05' W.

Consists of an atoll rim bearing a large number of islets. Rock (1916) states that there are about 52. The ring of islets is about 6.4 kilometers long and 2.4 kilometers wide.

The lagoon contains three large patches of deep water, of greatest depth over 40 meters, but the channels between the islets and the water covering the coral rock platform outside them are very shallow, so that it is pos-

sible to wade from islet to islet at low tide. The maximum elevation of the land surface is given in the "Pacific islands pilot" as 1.8 meters. Wentworth states that the islets consist entirely of detrital material without raised reef. This is for the most part loose, but particularly on the inner islet at the east end there are cemented sandstone and conglomerate. The island is richly vegetated. Rock (1916) records 13 species of flowering plants, including an endemic species of *Pandanus* and an endemic variety of another species of the same genus. It is possible that the endemic *Pandanus*, *P. rockii* Martelli, also occurs on Fanning and Washington Islands (Christophersen, 1927). There were probably coconuts on the island at the time of its discovery in 1802 (Emory, 1934). These coconuts were regarded as just recognizable as a form, *Cocos nucifera* f. *palmyrensis* Beccari (in Rock, 1916), which is, however, known elsewhere (e.g., Wilder, 1934) and was presumably introduced by Polynesian travelers. No archaeological material has been discovered. A large colony of *Sterna fuscata oahuensis* breeds on the low beach that constitutes Bird Islet. *Sula sula rubripes* and *Gygis alba candida* are clearly common in the trees. No land birds have been recorded. As Rock gives fairly complete notes on the common sea birds, it may be presumed that no terrestrial birds occur. Insects and spiders are said to be numerous, but little useful information is available. Rock states that in 1862 the Hawaiian Commission found a record on the island "that on the 19th day of October, A.D. 1859, the undersigned, Agent of the American Guano Co., landed from the brig Josephine, and having discovered a deposit of guano thereon, doth, on this 20th day of October aforesaid take formal possession of this Island, called 'PALMYRA' on behalf of the United States." The document is signed by G. P. Judd, Agent of the Company. Nothing more is known of commercial development of guano on Palmyra. It is not unlikely that the deposit discovered was a very superficial one, made by the sooty terns of Bird Islet.

Christophersen found that some parts of the coral surface beneath the soil mantle are phosphatized. Thus in the southwestern in-

terior part of Holei Islet, a very shallow layer of damp brown or black mold lies on a phosphatized coral hard-pan 10 to 20 cm. thick, containing about 40% PO_4 , 20% Ca, and little CO_2 , i.e., about 30% P_2O_5 and 28% CaO. This dark organic soil is acid (pH 5.0–6.5) and supports a forest of *Pisonia grandis* R. Brown and *Ochrosia oppositifolia* K. Schumann. In the eastern part of the same islet, where there is no phosphatic hard-pan, the soil, somewhat drier, is alkaline and contains less organic matter. The forest here is composed of *Pandanus rockii* and *Cocos nucifera* Linnaeus. Papala Islet has a practically pure stand of *Pisonia grandis* growing on a dark brown or black, acid, peaty mold, which gives strong reactions for Ca and PO_4 . Below this a phosphatized coral hard-pan is present. On Eastern Islet the whole forest consists of *Pisonia* (Rock, 1916), but no soil analyses are available.

A DRY ISLAND NORTH OF THE EQUATORIAL RAIN BELT

JOHNSTON OR CORNWALLIS ISLAND

LATITUDE $16^\circ 45' \text{ N.}$, LONGITUDE $169^\circ 32' \text{ W.}$

An atoll with two small islets. The larger is Johnston Island proper and the smaller, Sand Island. The islands have been greatly modified as a result of their use as an air base during the past war. The best available account of the island is contained in an article (Anon., 1945c) published in the New Yorker magazine, December 1, 1945. The larger island is about 800 meters long. The islands have stretches of coral and of sandy shore. The highest point, at the eastern end of Johnston Island, was originally 13.2 meters high (Bryan, 1942). According to the "Sailing directions" (United States Hydrographic Office, 1940) and the New Yorker article the island is formed of coral sand, bird bones, egg shells, and guano. It is reasonable to suppose that the major part is of the first-named material; elevated reef rock does not seem to have been recorded. The islands originally were covered with low vegetation, but only three species, *Lepturus repens* with scattered patches of *Tribulus cistoides* and small numbers of *Boerhaavia diffusa*, were present (Christophersen, 1931). The bird colony was evidently extensive but has not been described in detail. The New Yorker article

gives a vernacular list. Mr. William C. McGuire, of the staff of the magazine, tells me that this list is based in part on the British Admiralty Sailing Directions, and in part on information supplied by United States Navy personnel who had been stationed on the island. This list comprises *Diomedea nigripes* (goney), *Sula leucogaster* (brown booby), *S. dactylatra* (masked booby), *Anous* sp. (noddy), *Sterna fuscata* (wideawake), *Phaeton rubricauda* (red-tailed boatswain's bird), shearwaters, and moaning birds (? *Puffinus pacificus cuneatus*), and possibly rails. The last record seems doubtful. Bryan speaks of hundreds of individuals of a dozen species. The avifauna is evidently comparable to that of the Line Islands and Phoenix Islands with the addition of *D. nigripes*, but Johnston Island is apparently outside the range of the Laysan albatross, *D. immutabilis*.

Bryan says that from 1869 onward occasional cargoes of guano were removed, and that in 1909 the island was leased to a private individual who began systematic exploitation. The project was, however, soon abandoned, as the quality and quantity of the material were insufficient to pay for the work of collecting it. Jones (1946) says that a Mr. C. K. Ai of Honolulu was assigned the lease of the island in 1918 for the purpose of exporting guano. It is clear that although Johnston Island is climatically the Northern Hemisphere equivalent of the drier Line Islands, it cannot have accumulated guano in quantities approaching those that were found on Howland, Baker, or Jarvis Islands. This apparent difference is probably to be correlated with the evident low productivity of the Pacific north of the northern divergence.

WET ISLANDS TO THE SOUTH

Several islands in the wet zone from latitude 10° S. southward bore phosphatic guano. It is probable that the more important deposits were not of contemporary formation, as richly developed vegetation originally seems to have covered the islands. The separation of these localities from those in the Tuamotu Archipelago may be arbitrary. It is most unfortunate that so little is known about the deposits, which though of little commercial importance are of considerable scientific interest.

CAROLINE ISLAND

LATITUDE 10° 00' S., LONGITUDE 150° 14' W.

An elongated atoll about 9 kilometers long, bearing 24 islets, of which the northernmost, Nake Islet, and South Islet are the largest. The atoll is little known scientifically. A long account was given by Bennett (1840) which has been reprinted by Bryan (1939b). Bennett indicates that the interior of the islets was covered with *Tournefortia* and *Pandanus*. At least 27 species of flowering plants and ferns were found by the Eclipse Expedition of 1883 (Dixon and Trelease, 1884). It appears from Bennett's account that very numerous nests of *Sula s. rubripes* were present in the trees. Bennett adds that the "other species of birds of the coast were a kind resembling a coot, curlews and a species of Totanus" with legs of a "lemon-colour," while in "the Raiatean species they were blue. The island thickets contain a great number of small pigeons, with white head and neck, and the rest of their plumage a rich brown colour." It is not unreasonable to suspect that the "pigeons" were really *Anous minutus*, though they are also mentioned by Arundel (1890) to whom all terns were apparently "wideawakes." Dixon (1884) on the Eclipse Expedition, noted plover, herons, curlew snipe, two gulls (*sic*), noddy terns, and an all-white tern, clearly *Gygis alba*, gannets and boobies, presumably *S. sula* and *S. leucogaster*, and frigate birds. Dixon says that "Professor Holden reports hearing the notes of a singing bird." The ornithology of the island might repay further study.

The island was leased by Great Britain to Houlder Brothers and Company, of London, in 1872; according to Bryan some little amount of guano was dug. Qualtrough (*in* Holden and Qualtrough, 1884) noted in 1883 that "some varieties of phosphatic guano are found on the islets," but that at the time of his visit no effort to export the material was being made. J. T. Arundel took over the lease in 1881 and planted coconuts. The British Phosphate Commissioners kindly have supplied the following notes on two samples analyzed by A. E. Stephen:

- I. "Lab. no. 2.36. Samples taken by Mr. A. G. Bell, supercargo S. S. Emu—Sample of guano from heaps (about 120 tons) near

landing at Caroline Island 4/8/00. Rock received 29/9/00."

- II. "Sample of guano from surface rock, centre of home station at Caroline Island 4/8/00.' Received 29/9/00."

	I	II
Moisture	8.50%	5.00%
Organic matter	9.70	6.50
Carbonate	15.51	57.74
Phosphate	62.28	29.46

Privat-Deschanel (1910) lists Caroline Island as a phosphatized island. Unfortunately no other information about the deposits appears to exist.

FLINT ISLAND

LATITUDE 11° 26' S., LONGITUDE 151° 48' W.

An atoll about 2½ miles long and ½ mile wide, with a maximum elevation of 6.7 meters. The rainfall is evidently fairly high. The whole island is now cultivated, mainly as a coconut plantation. The island was densely wooded but without coconuts when discovered (Meinecke, 1876). The original vegetation is inadequately known. *Pisonia* and *Pandanus* are probably native (St. John and Fosberg, 1937). Guano was apparently stripped in some quantity prior to 1885 ("Pacific islands pilot," vol. 2, United States Hydrographic Office, 1926). The deposits appear to have been in the center of the island and midway between the center and the north end. Heiden reports that Flint Island guano was received in Hamburg in 1877 and 1878, the total quantity imported being 4266 tons.

Voelcker (1876) gives the following analysis:

H ₂ O and organic matter	13.26%
CaO	43.43
MgO, alkalis, SO ₃ , etc.	5.99
P ₂ O ₅	37.13
Insol. silica	0.19

MARGINAL CASES OF DEPOSITION IN FIJI

According to the "Pacific islands pilot" (United States Hydrographic Office, 1926) a few rocks near Lakemba Island in the Fiji group are white with guano. Thus Bacon Island (latitude 18° 02' S., longitude 178° 28' W.) is said to be a rock 18.3 meters high, white with guano. Two islets, Latei Viti and Latei Tonga, 18.3 meters and 15.2 meters

high within the Reid Reef (latitude $17^{\circ} 55'$ S., longitude $178^{\circ} 20'$ W.) are similarly described. There seems to have been no exploitation, and it is doubtful whether true accumulation of the material takes place.¹

DOUBTFUL AND APOCRYPHAL GUANO ISLANDS

On United States Hydrographic Office charts 824a and 825a, Suvarov Island (latitude $13^{\circ} 17'$ S., longitude $163^{\circ} 06'$ W.) is marked as yielding guano. It was also bonded and recorded as such in the United States Treasury. Suvarov Island is also listed as a guano island, along with the well-known islands described in the preceding parts of this work, by Privat-Deschanel (1910), but his statement implying that exploitation of these islands has in general hardly begun is so inaccurate that his mention of Suvarov does not justify the conclusion that it produced guano in the absence of any other good authority. The island was in fact leased to Lever Brothers in 1903 for the purpose of removing guano (Bryan, 1942), but there is no evidence that it was worked and the concern in question was doubtless primarily interested in copra production. No other indications of the existence of phosphatic material on this atoll exist, and the occurrence must be regarded as very doubtful. Suvarov consists of a number of islets and is wooded. Though the atoll is 15 kilometers across, the total land area is but 2.4 km². Sea birds are said to be very numerous (Bryan, 1942).

Tahiti, and possibly Upolu in British Samoa, should perhaps be added to the list of doubtful guano islands, for Heiden (1887) indicates that between 1875 and 1878, 1630 tons of phosphatic guano were received in Hamburg from Papeete on the former island, and 164 tons in 1880 from Apia, which may be the Apia on the latter island (p. 213). These cargoes may represent re-exported

material, or there may have been very small deposits, analogous to those of Fiji, on islets off Tahiti and the Samoan group. It is to be noted that G. C. Miller, British Consul at Tahiti, considered, as has been previously indicated (p. 182), that sea birds were scarce and that guano was unknown there.

In addition to the islands that have been mentioned, a number of atolls were bonded and registered with the United States Treasury as guano islands under the Guano Act of 1856. The full list is given in the New York Tribune, March 5, 1858, and has been reproduced by Behm (1859), Hague (1862), and by Bryan (1939a). An essentially identical list in the United States Treasury is given by Palmer (1900). Bryan (1939a) has moreover analyzed the list geographically, but without discussion of the occurrence of guano, though much valuable information about individual islands is given in his later publication (1942). Since it is of considerable importance, before proceeding to the argument of the general discussion, to have recorded all the central Pacific islands bearing phosphatic guano, every effort has been made to evaluate the claims of the existence of guano on each of the atolls listed. Power (1925), who had much practical experience with Pacific insular phosphates, says that every likely island has been examined two or three times. It is therefore evident that the islands listed below with the annotation "no independent record of guano," may certainly be regarded as lacking deposits in any general consideration of the distribution of insular phosphates of avian origin. It is clear that there were strong commercial inducements to bond and register islands as bearing guano when they in fact bore none, or did not even exist. Positions without comment are those of the "Pacific islands pilot," but where they are designated as "given" or "reported in," they are from Palmer's list.

AMERICA ISLAND: A synonym of Fanning Island (Bryan, 1939a); the whole group of Line Islands was often termed the America Islands.

ANNE ISLAND: Meinicke (1876) gives Anna as a synonym of Vostok, which fits the position given for Anne Island (latitude $9^{\circ} 48'$ S., longitude $151^{\circ} 15'$ W.), but for which there is no independent record of guano.

¹ It is evident from Zimmerman's (1948) account, published since the above was written, that some deposition occurs on Marotiri or Bass Rocks about 80 kilometers east of Rapa. Zimmerman says that the exposed rocks are colonized by "myriads of sea birds, and the deposits of excrement and bird remains are thick. However, we found there a dozen species of plants, some of them distinct new species. . . ." An earlier account (Zimmerman, 1936) indicates the presence of shearwaters and other species of sea birds.

ARTHUR (OR ARTHURS) ISLAND: Reported in the Tribune list at latitude $3^{\circ} 32' S.$, longitude $176^{\circ} 05' W.$, but not by Palmer. According to Bryan is a synonym of McKean.

BARBER ISLAND: Reported in the Tribune list at latitude $8^{\circ} 54' N.$, longitude $178^{\circ} 00' W.$, apparently non-existent.

BAUMAN ISLAND: According to Bryan, supposedly discovered by Roggeween in 1722 but apparently non-existent in the position given (latitude $11^{\circ} 48' S.$, longitude $154^{\circ} 10' W.$). Meinicke (1876) gives Bauman's Island as a synonym of Manua, Samoa.

DANGER OR DANGEROUS ISLAND: Presumably Danger Island (latitude $10^{\circ} 53' S.$, longitude $165^{\circ} 50' W.$), which is fairly near the position given (latitude $10^{\circ} 00' S.$, longitude $165^{\circ} 56' W.$) but for which there is no independent record of guano.

DANGERS ROCK: A synonym of Kingman Reef (latitude $6^{\circ} 25' N.$, longitude $162^{\circ} 24' W.$) which has a very little land surface in an unstable state and presumably is not a guano island; other imaginary dangers are reported in this region.

DAVID ISLAND: Apparently non-existent, at least in the position reported (latitude $0^{\circ} 48' N.$, longitude $176^{\circ} 10' W.$).

DUKE OF CLARENCE ISLAND OR NUKUNONO: (Latitude $9^{\circ} 10' S.$, longitude $171^{\circ} 53\frac{1}{2}' W.$), no independent record of guano.

FARMER ISLAND: According to Meinicke (1876) a synonym of Canton Island, which agrees tolerably with the position given (latitude $3^{\circ} 00' S.$, longitude $170^{\circ} 50' W.$). Bryan regards it as merely one of the Phoenix group.

FAVORITE ISLAND: Apparently non-existent in the longitude given (latitude $2^{\circ} 50' S.$, longitude $176^{\circ} 40' W.$). Meinicke mentions the name as a synonym of Canton Island. Bryan says that the history of the name is unknown to him but thinks the position implies one of the Phoenix Islands, probably Canton.

FLINT ISLAND: Reported in latitude $10^{\circ} 32' S.$, longitude $162^{\circ} 05' W.$, possibly a synonym of Rakahanga (Reirson Island); Flint Island in latitude $17^{\circ} 26' S.$, longitude $151^{\circ} 48' W.$ may be meant, though this is included in the list as Flints, at the right position.

FRANCES ISLAND: According to Meinicke,

Francis Island is a synonym of Rakahanga (Reirson) in latitude $10^{\circ} 02' S.$, longitude $161^{\circ} 5\frac{1}{2}' W.$, which agrees well with the position given (latitude $9^{\circ} 58' S.$, longitude $161^{\circ} 40' W.$). Bryan, however, thinks Frances may be the same as Tongareva in latitude $9^{\circ} 02' S.$, longitude $158^{\circ} 00' W.$

FRIENHAVEN OR TIENHOVEN: According to Bryan supposedly discovered by Roggeween in 1722 but apparently non-existent in the position given, latitude $10^{\circ} 00' S.$, longitude $156^{\circ} 59' W.$

GANGES ISLAND: Reported in latitude $10^{\circ} 59' S.$, longitude $160^{\circ} 55' W.$; apparently a synonym of Manihiki. Meinicke gives Great Ganges Island as a synonym of this island and Little Ganges Island as one of Rakahanga. Bryan accepts such an identification. The name has been applied to islands in other parts of the Pacific.

GRONIQUE ISLAND: According to Bryan supposedly discovered in 1722 by Roggeween, but apparently non-existent in the position given, latitude $10^{\circ} 00' S.$, longitude $156^{\circ} 44' W.$

HUMPHREY ISLAND OR MANIHIKI: (Latitude $10^{\circ} 23' S.$, longitude $161^{\circ} 01' W.$), no independent record of guano.

KEMNS (I.E., KEMINS) ISLAND: A synonym of Gardner Island, Phoenix group. No independent record of guano.

LIDERON OR SIDERON OR LIDEROUS ISLAND: Reported in latitude $11^{\circ} 05' S.$, longitude $161^{\circ} 50' W.$, probably a synonym of Manihiki (Bryan, 1939a). Meinicke also reports Liderous Island as an alternative name for that island.

LOW ISLAND: Reported in latitude $9^{\circ} 33' S.$, longitude $170^{\circ} 38' E.$ According to Bryan is a synonym of Fakaofu or Bowditch Island, from which there is no independent record of guano. Meinicke gives Low as a synonym of Starbuck (latitude $5^{\circ} 38' S.$, longitude $155^{\circ} 53' W.$).

MAKIN (MACKIN) ISLAND OR TARITARI: (Latitude $3^{\circ} 05' N.$, longitude $173^{\circ} 20' E.$), no independent record of guano. Palmer gives the longitude as $172^{\circ} 46' W.$

MARY LETITIA ISLAND: A synonym of Gardner Island (Meinicke) from which there is no independent record of guano. Bryan thinks it is either Hull or Gardner Island.

MATTHEW ISLAND OR MARAKI: (Latitude

1° 58' N., longitude 173° 20' E.), no independent record of guano.

NASSAU ISLAND: (latitude 11° 33½' S., longitude 165° 25' W.), no independent record of guano.

PENRHYN ISLAND OR TONGAREVA: (Latitude 9° 00' S., 158° 00' W.), no independent record of guano.

PESCADO ISLAND: A synonym of Manihiki, according to Meinicke (1876). Bryan regards the island as not identifiable in the position given, latitude 10° 38' S., longitude 159° 20' W.

QUIROS ISLAND: Reported in latitude 10° 32' S., longitude 170° 12' W., is according to Bryan (1939a) a synonym of Swains Island, from which there is no independent record of guano.

REIRSON ISLAND OR RAKAHANGA: (Latitude 10° 02' S., longitude 161° 05½' W.), no independent record of guano.

ROGEWEIN ISLAND: According to Bryan, supposedly discovered in 1722 by Roggeween but apparently non-existent in the position given (latitude 11° 00' S., longitude 156° 07' W.). Several apocryphal atolls appear to have been reported between Flint Island and Manihiki.

SAMARANG ISLAND: A synonym of Palmyra (Meinicke, 1876, p. 433; Bryan, 1939a), though it often appeared on maps as an independent, though non-existent, island.

SARAH ANNE ISLAND: Reported in the Treasury list at latitude 4° 00' N., longitude 162° 20' W. The Times Atlas and Gazetteer gives this island at latitude 4° 35' N., longitude 153° 20' W. According to the United States Hydrographic Office Bulletin (1937) it could not be found in 1874, nor does it figure in any reports of the numerous scientific studies made in this region in the present century. It is supposed that the latitude given may be an error for 4° 35' S. and that Malden Island may be meant. In spite of its interesting position, Sarah Anne must be regarded as mythical.

SHAW'S ISLAND: Certainly produced guano, as Voelcker (1876) records material containing 34.69% P₂O₅. He says that the island is near Malden, but it has not been possible to identify it further.

STAVER ISLAND: A synonym of Vostok (Meinicke, 1876; Bryan, 1939a) from which

there is no independent record of guano.

WALKER ISLAND: Reported in latitude 3° 58' N., longitude 149° 10' W., and included in the Times Atlas and Gazetteer in practically this position, is not noted in the "Pacific islands pilot" or in recent literature on the region and, like Sarah Anne, must be reluctantly abandoned. Bryan thinks it a synonym of Fanning Island.

It may be noted that Teinhoven (= Fienhaven), Rogewein, and Bauman were leased by the British authorities to the Hon. W. L. Crowther in 1865, but the license was revoked in 1869 on the grounds that the islands could not be found and that the stipulated amounts of guano had not been removed from them (Crowther, 1939).

When figure 46 showing the correlation of hydrography with phosphate deposition was prepared, Victoria Island, regarded as doubtful in the first edition of the "Pacific islands pilot" (United States Hydrographic Office, 1916b), included in the key chart but no longer treated in the text of the third edition (*ibid.*, 1926), and entirely omitted in the fifth edition (*ibid.*, 1940), was excluded as non-existent.

ATOLLS WITHOUT PHOSPHATIC DEPOSITS

Atafu, Nukunono, and Fakaofu, the three atolls of the Tokelau or Union group, have large lagoons and narrow rims bearing numerous small islands. All are moderately moist, inhabited and well cultivated. The same general characters are shared by Danger Island or Pukapuka, Manihiki, Rakahanga, Tongareva, and Suvarov. Since all these are unfavorably shaped to retain guano, the absence of valuable deposits is not very remarkable, though there is a small quantity of guano on the similar but drier Phoenix atolls such as Canton. The absence of workable deposits from the next three islands is more interesting.

SWAINS ISLAND OR OLOSENGA

Also known as Quiros Island or Gente Hermosa, a slightly emergent atoll about 2.4 meters long with a complete land rim up to about 6.1 meters high. If the island was the Isla de la Gente Hermosa discovered by Quiros, it was certainly inhabited early in the

seventeenth century. It appears that the inhabitants were killed or carried off by a raid from Fakaofu shortly after, and that there was no further successful settlement until 1856. The island is very densely vegetated. It seems reasonably certain that if any extensive phosphatic deposit existed it would have been discovered. In form the island is not unlike Phoenix or Sydney Island, and it is therefore natural to suppose, had it lain 10° farther north it would, like them, have been a guano island.

NASSAU ISLAND

LATITUDE 11° 34½' S., LONGITUDE 165° 25' W.

A small, oval, emergent atoll about 1200 meters long, with the lagoon represented by a swampy area containing fresh water. It appears to have been inhabited intermittently (Bryan, 1942), at least since the seventeenth century, but no extensive settlement seems to have existed. Sea birds are said to be present but not common. The island is richly vegetated, with *Pisonia*, *Cordia*, and *Calophyllum* as well as coconuts and various herbs and ferns. The island was claimed as a guano island, but there is no evidence that it contained any deposits.

VOSTOK ISLAND

LATITUDE 10° 05½' S., LONGITUDE 152° 23' W.

A triangular, emergent atoll about 1200 meters long. It is little known and has apparently never been permanently inhabited. The greater part of the island is covered with a dense, virgin *Pisonia* forest on which myriads of sea birds are said to breed (Fosberg in Skottsberg, 1940). There are a gravelly beach and a sunken reef around a large part of the island which make landing difficult. Since Vostok was claimed as a guano island it seems improbable that any deposit of significance would have remained unexploited. The loading of boats would probably have been difficult, but this was true also at several of the Phoenix Islands. Phosphatic soils no doubt are developed.

PHOSPHATIC SOIL ON ROSE ATOLL

In the previous discussion reference has

primarily been made to phosphatic deposits of considerable extent and high purity, often overlying phosphatized coral rock. The chief criterion of the existence of such deposits has been their commercial exploitation. It is, however, obvious that wherever sea birds rest or breed, some phosphate formerly in the ocean will be delivered to the land. A complete series of intermediate conditions must exist between a little white film of droppings present around nesting sites during part of the year and the great deposits that probably contained hundreds of thousands of tons, as, for instance, that of Malden Island. It is a matter of importance in discussion of guano deposits as paleoclimatic indicators to gain some idea of the effect of bird droppings on the land surface of relatively wet regions not having commercially significant deposits. The most interesting and important cases are those of wet, richly vegetated islands on which large bird colonies nest in trees. Only one locality has yielded the requisite information, though Christmas Island, were it better investigated, would probably give similar results.

ROSE ATOLL

LATITUDE 14° 33' S., LONGITUDE 168° 08½' W.

A small quadrangular atoll 125 kilometers from Tau Island in the Manua group. The atoll ring bears two islets. One of these islets, Sand Islet, is bare and unstable; the other, Rose Islet, is 3.4 meters high. Rose Islet contains emergent lithothamnium reef and has a rich stand of *Pisonia grandis* trees, on which boobies (presumably *S. s. rubripes*) breed. The *Pisonia* stand is apparently at least a century old and doubtless is much older.

The islet has been described by Mayor (1924), by Setchell (1924), and by Lipman and Shelley (1924) from Mayor's collections. The soil in the *Pisonia* stand is described as dark brown when dry, black when wet, and "much like a peat of calcareous origin." Beneath this soil is a layer of partially decomposed lithothamnium masses with a high percentage of pore spaces. This material is apparently much mixed with organic matter. Below this lies lithothamnium rock. The following analyses are given by Lipman and Shelley, and also quoted by Setchell:

	SOIL	INTER-MEDIATE LAYER	LITHOTHAMNIUM ROCK
H ₂ O at 100° C.	5.12%	2.49%	0.4%
Ignition loss ^a	22.84	31.09	46.22
SiO ₂	0.18	0.2	0.16
Al ₂ O ₃	16.717	9.2	0.465
Fe ₂ O ₃	0.4	0.48	—
P ₂ O ₅	20.94	14.599	0.575
P ₂ O ₅ sol.	0.447	0.449	—
CaO	29.26	35.776	44.008
MgO	1.745	3.338	7.457
SO ₃	1.144	0.871	0.611
Na ₂ O	1.38	1.389	0.348
K ₂ O	0.228	0.229	0.155
Cl	0.874	0.106	—

^a = CO₂, organic and combined water.

The great enrichment of aluminum in the surface layer, of the order of forty-fold, is interesting, particularly as it is apparently not accompanied by any enrichment of iron. Much silica and some magnesium are obviously lost in the process of formation of the inorganic residual part of the soil from the limestone. The loss of silica and enrichment of alumina are of course characteristic of tropical pedogenesis. Lipman and Shelley think that in the present case ammonia from bird droppings removed the silica as ammonium silicate. They also consider that the phosphate is derived from the parent rock by a concentration process similar to that causing enrichment of aluminum. It is, however, reasonable to suppose that a notable proportion of the phosphate is derived from bird droppings.

It is evident that much of the calcium in the soil is present as phosphate, though aluminum phosphate may well be present. There are said to be fragments of lithothamnium rock in the soil, but in the absence of separate CO₂ and organic determinations it is impossible to ascertain the probable mineralogical composition of the material analyzed. It is reasonable to suppose that the soil is alkaline. The phosphate content obviously falls off and the carbonate content increases with increasing depth. The light intermediate material with a large volume of pore spaces clearly does not represent a hard-pan. The profile on Rose Islet may be instructively compared with that in the *Pisonia* forest on Palmyra, in which an acid organic soil lies on a phosphatic hard-pan which

seems to contain about 58% calcium phosphate, part perhaps as CaHPO₄ and with very little carbonate. It is plausible to suppose that the profile on Rose Atoll represents phosphatization due to concentration of phosphate in the parent rock, presumably with enrichment from the boobies nesting in the trees, while the Palmyra profile represents a *Pisonia* stand growing on the site of a preëxisting guano deposit. If this interpretation is correct, it has great implication, developed below. It is therefore important that future investigators should pay special attention to soil profiles of the kind found on Rose Islet. There must be a great number of localities throughout the tropical oceans where no commercial phosphate occurs but where forest on coral reef is occupied by nesting sea birds. A great many more studies of the kind made by Mayor are therefore possible and would throw light on the conditions on Palmyra. It has already been indicated that such phosphatic soils probably occur on Christmas Island. The fertility of many wet atolls doubtless depends on such phosphatization, followed by bacterial nitrogen-fixation, as seems to be the case on Rose Islet (Lipman and Shelley, 1924). The whole problem therefore is not only of climatological interest but of botanical and agricultural significance also. The possible role of excess phosphate, in regulating competition between *Pisonia grandis* and other trees, adumbrated by Christophersen, would also repay further study.

THE TOTAL QUANTITY OF GUANO

The data presented above suggest the very approximate estimates, given opposite, for the phosphorus deposited on the islands which were still accumulating guano when exploitation began in the nineteenth century.

The details on which these estimates are based are all set out above. Comparison of the figures with the facts on which they are based will show how unsatisfactory some of the estimates are. Nevertheless, the available information does point to some figure not much below 200,000 tons for the whole phosphorus deposited on the drier Line and Phoenix Islands. In addition an allowance of about 5300 tons P may be made for Fanning Island, and since Washington and Palmyra

ISLANDS	TONS	PERCENTAGE OF P	EQUIVALENT OF P IN TONS
Howland	124,000	14.9%	18,500
Baker	ca. 250,000	15.8	39,400
Jarvis	ca. 250,000	15.0	37,500
Malden	ca. 400,000	12.5	50,000
Phoenix group:			
Enderbury	ca. 100,000	ca. 15	15,000
McKean	ca. 30,000	12.5	3,800
Other islands, arbitrary allowance			2,500
Starbuck	ca. 50,000	14.7	7,400
Total			174,100

have small deposits, 6000 tons P for the wetter Line Islands is not an unreasonable estimate.

TIME RELATIONS OF DEPOSITION

The only direct observation that is available relates to an unidentified island. Ledoux (1890) writes, "I was personally acquainted with an intelligent captain who was sent to a coral island in the South Pacific for a cargo of guano. The island was uninhabited, and the birds were there in countless swarms. The same captain had been there twenty years before, and the place had been unvisited since that time. On this former trip his men had built a hut of coral rock, after cleaning off a space for it, and covered it with a piece of sail, as a shelter during their stay. On leaving, they took away the sail and left the 'hypæthral' hut with its board flooring. On returning after twenty years, the fresh deposit had accumulated within the hut to a depth of twenty inches—showing a rate of about one inch per annum—while the underlying coral limestone was altered to phosphate for several feet, gradually passing into carbonate in going down." It seems probable that this account refers to one of the Line or Phoenix Islands. The phosphatization of the coral had probably occurred before the cleaning of the space for the hut. The rate of deposition of 2.5 cm. per annum implied by this account is of the same order of magnitude as the rate deduced for the Peruvian islands from archaeological evidence. The two estimates are, however, really not comparable. On the Peruvian islands deflation is the only likely important mode of loss, while on the Pacific islands the main loss is certainly due to decomposition of organic compounds and

leaching of some of the phosphate, which must be in part retained in the phosphatization of coral rock.

In contrast to this statement is the opinion expressed by Emory that the ruins on Malden Island, which perhaps date from the eighteenth century, may stand on phosphate, though none are covered by guano. It is, however, certain that the Malden bird colony had been much reduced, not merely since European introduction of cats, but in all probability since the first Polynesians landed on the island. Emory's rather uncertain remarks therefore probably have no chronological significance.

Apart from these unsatisfactory scraps of dubious information, an indirect approach to a chronology can be made by comparison with the maximum rate of phosphate deposition elsewhere. For this purpose the estimates for Howland and Baker Islands may be considered. No data on the area of the Malden deposit exist and for Jarvis much phosphate appears to exist below the level reached by guano diggers. The available figures are:

ISLANDS		PRE-LIMINARY ESTIMATE (IN TONS) IN RE- PORTS TO STOCK- HOLDERS		MAXIMUM ESTIMATE (IN TONS) OF MA- TERIAL EXPORTED	
Howland	$1.62 \times 10^6 \text{ m}^2$	3,000,000		124,000	
Baker	$1.34 \times 10^6 \text{ m}^2$	7,000,000 +		312,000	

The estimates of phosphate per unit area, assuming 40% of the material to be P_2O_5 and half the area of the island to be phosphatized, are:

ISLANDS	INITIAL ESTIMATE (IN KG. PER M ²)	MAXIMUM ESTIMATE (IN KG. PER M ²) OF EX- PORTED MATERIAL
Howland	1480	61
Baker	4180+	186

The true values are certainly nearer the lower estimates than the upper. The Howland value of 61 kilograms per m² is doubtless nearly correct, and 200 kilograms per m² would be a good estimate for Baker. When these figures are compared with the 1500 kilograms of P₂O₅ per m² that accumulated on North Chincha Island, it is abundantly clear that unless the bird colonies were immensely less on Howland and Baker than on the Peruvian islands, no more, and indeed probably much less, time is needed to have produced the observed phosphatization on the dry Line Islands than was required to produce the Peruvian deposits. The guano birds on the Peruvian islands certainly breed in much denser colonies than any birds likely to have occurred on the Pacific islands, and the lower and more probable estimates of phosphatization are much less than the figure for North Chincha Island. Basin-shaped atolls are, however, probably more favorable for retention of insoluble material than are the Peruvian islands where deflation may well play an important role in reducing the rate of accumulation. Where the initial phosphatization of the coral had occurred it is moreover unlikely that any great loss of phosphate in solution took place. It is certainly reasonable to suppose that phosphatization on Baker and Howland Islands has proceeded for but a few millennia.

CLIMATIC HISTORY OF THE LINE AND PHOENIX ISLANDS

All the Line Islands, save Palmyra, and presumably at least those members of the Phoenix Islands that have closed lagoons show evidence of emergence of the order of 3 m. Palmyra alone appears to be composed solely of detrital material piled up on an unelevated lagoon rim (Wentworth and Palmer, 1925; Wentworth, 1931). The emergence is believed by Wentworth and Palmer to be due to a small eustatic fall in the level of the

oceans in post-Pleistocene time, though an alternative explanation, based on the plastic readjustment of the ocean floor to its post-glacial load of water, is given by Daly (1934). A similar fall can be traced throughout a large area of the central Pacific. The meaning and date of the event producing the emergence are therefore rather uncertain; it is, however reasonable to regard it as having occurred in relatively recent times. Wentworth points out that Palmyra either did not exist at the time of the emergence or, emerging as a very incomplete atoll rim, was cut away, leaving only detrital material. The latter interpretation is certainly the most reasonable. Whatever interpretation is adopted, such phosphatization as occurred on Palmyra obviously took place subsequent to the emergence. A bird colony must have occupied the newly formed surface for a sufficient time to produce the phosphatization observed by Christophersen. The profile at Rose Atoll strongly suggests that, though a phosphatic soil might result from a bird colony nesting on a richly vegetated island, the phosphatic hard-pan observed on Palmyra would not develop. Moreover it seems unlikely that an island without a closed lagoon would become phosphatized under the present meteorological conditions of Palmyra, even if a forest cover had not been immediately established. The most reasonable explanation of the Palmyra phosphatization would seem to be that the climate was drier at some time after the emergence. The same reasoning might perhaps be applied to the Fanning Island phosphate deposit, if more was known of it. It seems unlikely that phosphatization would have occurred on Fanning and not on Christmas Island under present meteorological conditions, yet it is certain that a workable deposit did occur on Fanning, and very uncertain that any phosphatization other than the formation of phosphatic soils occurred on Christmas Island. Washington Island with its closed lagoon is clearly a special case. Its history may have been comparable to that of Clipperton Island, in which the lagoon has become closed off and freshened during the past century. The archaeological evidence seems to suggest that the Washington peat bog is not many centuries old, and the freshening of the lagoon,

perhaps, as Elschner suggests, as the result of phosphatization, cannot have occurred at a much more remote time than the initiation of the growth of the peat.

The whole history of the northern Line Islands could be explained by the hypothesis that the equatorial rain belt formerly lay somewhat farther south, with its center over Christmas Island rather than over Washington. Washington might have had some water in the lagoon, but this could have been brackish and without a marginal zone of peat. Fanning and Palmyra being somewhat drier than they are today would more easily acquire phosphatic guano; Christmas Island being wetter would acquire none. The three dry islands on the Equator may have been wetter, but if the shift of the rain belt to its present position occurred a few thousand years ago there would be ample time for ac-

cumulation of the deposits found in the nineteenth century. This interpretation is put forward simply as a working hypothesis; it may have to face insuperable climatological difficulties. It must, however, be pointed out that the postulation of a northward shift of the mean thermal Equator, from a more southerly position, seems to be necessitated by the Peruvian data already considered, and there is nothing in the rather vague chronology that can at present be developed to exclude the identity of the shifts postulated to explain the distribution of old and contemporary guano deposition both in the central Pacific and on the Peruvian coast. The alternative hypothesis of a post-Pleistocene dry period throughout the whole Pacific fits the special case of the Line Islands less neatly, but must be considered below in relation to the western Pacific islands.

AN ATOLL IN THE EASTERN PACIFIC

CLIPPERTON ISLAND

LATITUDE $10^{\circ} 17' \text{ N.}$, LONGITUDE $109^{\circ} 13' \text{ W.}$

The only atoll in the eastern Pacific and a remarkable island in other ways. Though worked for phosphate intermittently at least from before 1898 to 1914, it has been seldom visited by scientific travelers, being "a dangerous place at the best of times" which "should always be approached with great caution" ("Mexico and Central America pilot, west coast," United States Hydrographic Office, 1920c).

The atoll rim is elliptical, about 3.6 kilometers long in the major northwest-southeast axis, and about 2.6 kilometers wide (fig. 53). There is a fringing reef around the land rim, best developed on the southwest side and partly uncovered at low water. The land rim is described by the "Mexico and Central America pilot" as of sand-like appearance. Snodgrass and Heller indicate a width of from 60 to 400 meters. They say that the entire rim, except for the trachyte rock, is composed of irregular fragments of coral and that where sections of the bank of the rim have been cut by water the deeper material is seen to be like the superficial but more compact. No coral sand was observed. There is no evidence of raised reef *in situ* in any re-

port on the island. The maximum elevation of the land rim is given on Wharton's (1898) map as 14 feet (4.3 meters), but the "Pilot" gives 8 feet (or 2.4 meters) as the greatest



FIG. 53. Map of Clipperton Island. After Wharton.

height of the coralline material. The most remarkable feature of the island is a great trachyte rock, 19 meters high, that stands up on the inner side of the land rim on the south-eastern side of the island.

The rim is now quite complete, two passages into the lagoon that existed in 1840 having been blocked by the piling up of coral sand prior to 1898 (Wharton). The lagoon evidently has a very irregular floor. Wharton's chart gives soundings apparently made by P. J. Henning in 1897 (Snodgrass and Heller, 1902), which, however, he seems to regard as unreliable. The greatest depth recorded corresponds to 100 meters, but Wharton was informed by J. T. Arundel that the greatest depth he could find was 37 meters (20 fathoms), though 48 meters (26 fathoms) had been reported by a man on the island.

There has clearly been some misunderstanding about the climate of Clipperton Island, particularly in the ornithological literature. Snodgrass and Heller (1902) say that the island is hot and very humid. Murphy (1936), however, speaks of Clipperton as a dry island. He points out that the brown booby of Cocos Island is *Sula leucogaster etesiaca* of the humid Colombian coast, whereas on Clipperton he supposed that *S. l. brewsteri* of the arid California coast occurred. More recently Wetmore finds the Clipperton bird, *S. l. nesiotes* Heller and Snodgrass, to be distinct from *brewsteri* though apparently identical with that from the dry Las Tres Marias Islands and Isabella Island.¹ The conflicting ideas of the climate of Clipperton are probably due to the fact that the rainfall is markedly seasonal. The "Mexico and Central America pilot" states that the dry season extends from December to May and that in the wet season waterspouts break on the southwest side of the island. The "Atlas of climatic charts of the oceans" (McDonald, 1938) indicates that from December to May the island lies just inside the frequency isogram indicating that 5% of the observations at Greenwich Mean noon record steady rain, while from June to August the island is be-

tween the isograms for 10% and 15%, and from September to November on or very close to the isogram for 10% of the observations recording steady rain. Snodgrass and Heller visited Clipperton on November 23-24, 1898, evidently at the end of the rainy season. Though Morrell (1832, p. 219) mentions a little shrubbery, some coarse grass, and an urticant plant resembling sarsaparilla, Wharton (1898) and Snodgrass and Heller (1902) speak of Clipperton as entirely devoid of vegetation. This condition was attributed to the vast number of birds, and by Snodgrass and Heller to the large population of land crabs also, "birds and crabs are everywhere so abundant that no plant could possibly grow there unless artificially protected." Comparison with Palmyra Island, which lies on or within the isogram for 10% of the observations recording steady rain for three-quarters rather than for half the year, suggests that although the biological factors indicated by Snodgrass and Heller are doubtless of primary importance in preventing establishment of vegetation they might be less effective if Clipperton Island were wetter throughout the first half of the year. The island is at present certainly not entirely devoid of vegetation; Killip (1939) records *Phyllanthus niruri* Linnaeus, *Heliotropium curassivicum* Linnaeus, and *Solanum nigrum* Linnaeus. All are species of immense distribution, doubtless introduced by man in recent years. A single palm and a group of low bushes near the landing on the northeast side of the atoll are indicated in a photograph taken on President Roosevelt's cruise in 1938 and published by Schmitt (1939). It is possible that the establishment of an adventive flora has been facilitated by the reduction in numbers of the land crabs, *Gecarcinus planatus* Stimpson, which has apparently occurred since Snodgrass and Heller visited the island. Schmitt attributes this decrease in land crabs to the drove of pigs that now exist on the island.

The lagoon, now closed, has clearly become much diluted by rain water. Snodgrass and Heller and the "Mexico and Central America pilot" both describe it as brackish, and the latter authority adds that it smells strongly of ammonia during the dry season. Surf is known at times to break over the land rim, so that some salt water as well as rain water

¹ *S. l. albiceps* Van Rossem, from Las Tres Marias and Isabella Islands, is regarded as identical with *S. l. nesiotes* by Wetmore. The supposed characters of *albiceps* are very slight differences in measurement. It is anyhow unlikely that the correlation of subspecies with climate indicated by Murphy is valid in this case.

still must enter the lagoon. *Najas marina* Linnaeus, normally a brackish-water plant, occurs in it, as does an undetermined species of *Chara*. There is an extraordinary algal flora, the existence but not the nature of which was indicated by Snodgrass and Heller. It consists of *Lyngbya versicolor* (Wartmann) Gomont in great abundance, *L. aestuarii* (Mertens) Liebmann, *L. lagerheimii* (Mobius) Grunow, and *Calothrix stellaria* Bornet and Flahault representing the Myxophyceae, and two forms of *Closterium parvulum* Nägeli, one near var. *majus* West, *Cosmarium clippertonensis* Taylor, *C. subprotumidum* Nordstedt forma, *Oocystis solitaria* Willrock, near f. *major* Wille, and *Oedogonium* sp. representing the Chlorophyceae. No diatoms seem to be recorded. The presence of desmids strongly suggests the water to be almost fresh. The large quantities of *Lyngbya* clearly reflect eutrophication of the lagoon by material washed from bird droppings. Apart from birds, the fauna consists of a supposedly endemic lizard, *Emoia arundeli* (Garman), which is but doubtfully distinguishable from *E. cyanura* (Lesson), a widespread Pacific form (Schmidt in Burt and Burt, 1932), a damselfly, a cicindelid beetle, and a few flies. Snodgrass and Heller indicate that the most abundant bird breeding on the island is *Sula dactylatra* (sub *cyanops*). The subspecific status of the birds of this colony does not seem to be certain, though *S. d. californica* occupies the nearest stations to Clipperton. Immense numbers were present in November, making slight depressions in the coral sand as nests. The species is, however, not enumerated by Wetmore (1939) in his report on the birds collected on the island in July during the Presidential cruise of 1938. *S. sula* naturally does not occur on an island lacking vegetation, while *S. leucogaster nesiotes* is evidently much less abundant than *S. dactylatra*, at least in November. Apart from boobies the commonest birds appear to be sooty terns, *S. fuscata crissalis*, breeding on small islands called the Egg Islands in the northwestern part of the lagoon, and noddies, *Anous stolidus ridgwayi*, breeding mainly on the trachyte rock. *Anous minutus diamesus* (Heller and Snodgrass) has been recorded from Clipperton both by Heller and Snodgrass and by Wetmore; the former found only immature females and one half-grown

bird. The last record presumably indicates nidification, but there are no details available as to its nesting site. A frigate bird that does not appear to be adequately identified in the literature, and *Gygis alba candida* complete the list of Clipperton sea birds. Morrell noted a few small land birds, which he supposed, probably correctly, to have been blown from America.

It is evident from Snodgrass and Heller's account that the three most abundant species, *Sula dactylatra*, *Sterna fuscata crissalis*, and *Anous stolidus ridgwayi*, were all breeding late in November. From Wetmore's account it appears that young in down, of various ages, of *S. leucogaster nesiotes* are present in July. Wetmore noted two young of *Anous stolidus ridgwayi* just attaining first autumnal plumage in July. It is thus apparent that breeding begins on Clipperton Island at the close of the rainy season and that the major part of the rearing of young birds occurs early in the dry season.

The broken coral rock of the atoll rim has in places been transformed into large beds of calcium phosphate that have been worked commercially (Wharton, 1898; Snodgrass and Heller, 1902; Elschner, 1913). Exploitation by the Pacific Islands Company began in 1898 (Snodgrass and Heller) and continued until 1914, although some inhabitants of the settlement remained until 1917 (United States Hydrographic Office, 1920c). Though the poor landing may have limited output, the long period of operation suggests an initially large deposit. Material examined by Elschner in Honolulu consisted in part of a white, chalk-like substance and in part of yellowish gray, coarse powder. Snodgrass and Heller were told that the material exported contained 70% to 80% phosphates. The only analysis that has been published is by Gilbert (1896), who found:

H ₂ O	3.80%
Organic	4.83
CaO	49.31
MgO	0.25
(Al,Fe) ₂ O ₃	0.04
P ₂ O ₅	36.06
CO ₂	2.96
SO ₃	0.46
SiO ₂	0.28
NaCl	0.15

If, following Gilbert, the carbonate and sul-

phate be regarded as calcium salts and the small amount of magnesium as phosphate, the corrected molecular ratio $\text{CaO}:\text{P}_2\text{O}_5$ is 1:0.312, presumably implying an apatite-like material.

The trachyte rock, the principal breeding place of the noddies, is dissected into numerous pinnacles and its interior hollowed out into caves and large passageways, extending throughout the mass. Snodgrass and Heller say that the rock is so worn by water that it looks like an isolated block of sandstone. In places it is decomposed into a soft whitish material, while in other places the guano has produced a white glaze. The general characteristics of the rock as observed by Snodgrass and Heller are well shown in the photograph published by Wharton and here reproduced (pl. 14, fig. 1). Teall (1898) examined five hand specimens of the rock petrographically and made analyses of three of them. The least-altered (I) rock consisted of phenocrysts of sanidine set in a ground mass of

microlithic feldspars and brown interstitial matter. A second specimen, while retaining the structure of the trachyte with comparatively unaltered phenocrysts, showed greater chemical change (II) in the ground mass, while in a third (III) the phenocrysts have largely disappeared, and both ground mass and much of the sanidine have been replaced by a white or cream isotropic substance. Analysis showed clearly the replacement of silicate by hydrated phosphate.

	I	II	III
SiO_2	54.0%	43.7%	2.8% (+2.2% insol. HCl)
P_2O_5	8.4	17.0	38.5
Al_2O_3	17.9	—	25.9
Fe_2O_3	4.4	—	7.4
CaO	1.4	—	—
K_2O	4.5	—	—
Na_2O	5.0	—	—
Ignition loss	3.8	12.3	23.0

THE HAWAIIAN LEEWARD ISLANDS

The Hawaiian Leeward Islands consist of a chain of small islands and reefs (fig. 54) stretching from the main archipelago in a northwesterly direction. The elevation of the members of this chain in general decreases from east to west. The four eastern islands or island groups, Nihoa Island, Necker Island, French Frigate Shoals, and Gardner Island, with which Kaula in the main archipelago may be associated, are wholly or in part volcanic. Laysan Island and Lisiansky Island are slightly elevated atolls. Pearl and Hermes Reef, Midway Island, and Ocean Island are atolls with little land surface.

OCEANOGRAPHY

The circulation of the northern part of the central Pacific is more complicated than that of the southern part and is less well understood. A good general summary is given by Sverdrup, Johnson, and Fleming (1942). The North Pacific Current flows eastward in about latitude 37° N. from the southern shores of Japan, but on reaching about longitude 160° W. it turns south, to join the North Equatorial Current. Circulation between latitudes 15° N. and 30° N. in the region east of longitude 165° W. is dominated by a clock-

wise gyral, the center of which lies northeast of the Hawaiian Islands. It seems possible that there is some upwelling on the western side of this gyral. There is probably considerable seasonal variation in the disposition of these current systems, and the surface movements of the ocean may be largely controlled by winds and have no clear relation to the main hydrographic pattern.

CLIMATOLOGY

The islands lie on the northern margin of the northeast trade-wind belt. Typically easterly winds of constant direction and high velocity are, however, well marked only during the summer, being most developed in July. Regular observations of temperature and precipitation are available only for Midway Island. The annual mean temperature is here 21.9° C., the recorded extremes being 7.8° to 32.8° C. February is the coolest month, with a mean temperature of 18.2° C., August the warmest, with a mean temperature of 25.8° C. Comparison with sea-level stations on Oahu and Hawaii indicate that such temperatures are likely to prevail throughout the group (Reed, 1927).

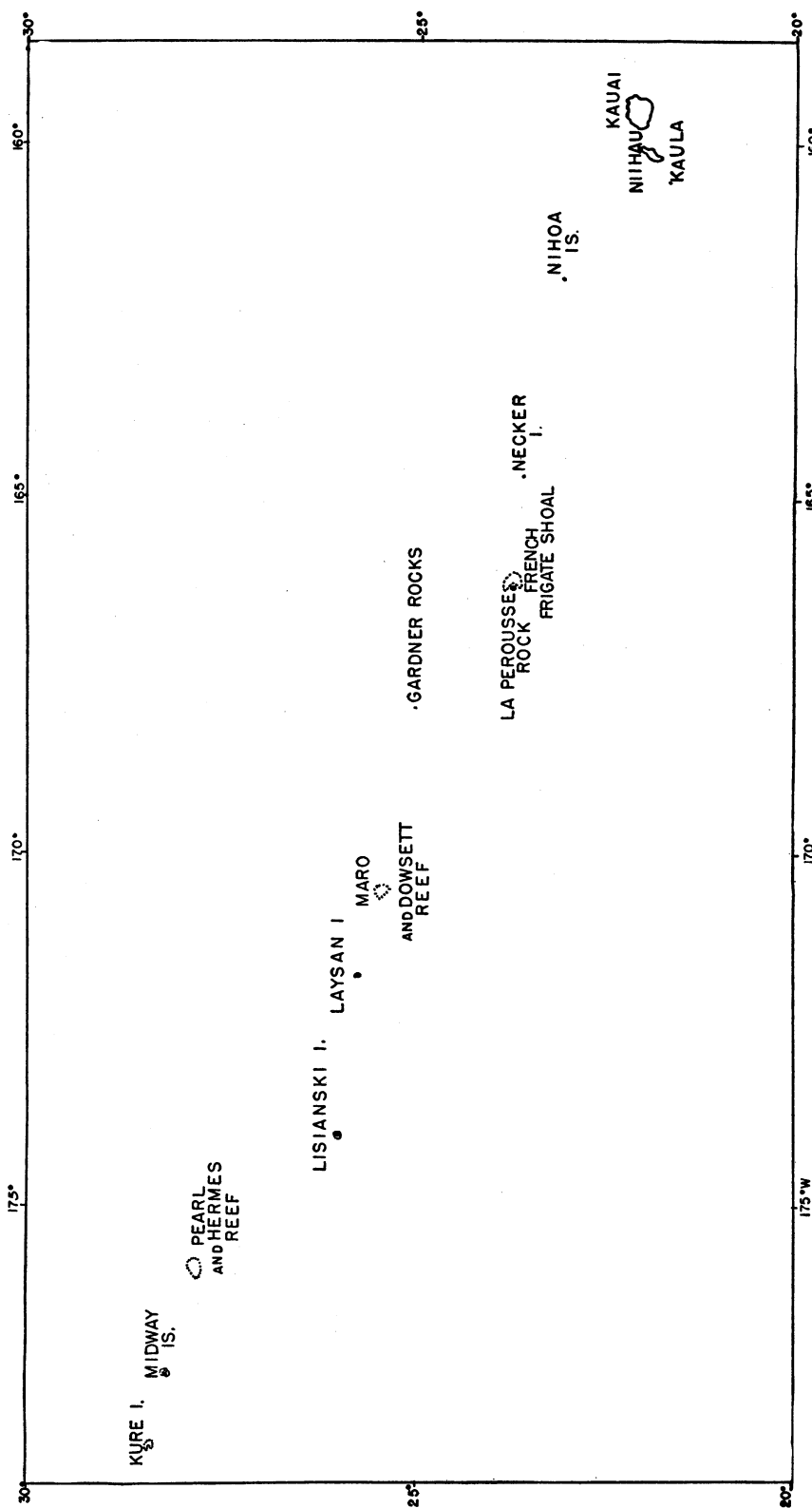


Fig. 54. Map of the Hawaiian Leeward Islands.

The precipitation at Midway is given as 1092 mm. per annum. Only November (44.2 mm.) is recorded as having less than 50 mm. per month. October is the wettest month with 132 mm. Days with 44 mm. or more rain have been recorded in every month. The summer (May to October) mean rainfall is 51.6% of the total. Comparison may be made with Kealia, on the eastern coast of Kauai, and with Waiawa, on the southwestern coast of the same island. The former station has a mean annual rainfall of 1038 mm., the latter of 564 mm. Both localities have marked seasonal variations with minimal rainfall in June, July, and August. Though this is more marked at Waiawa, which lies in a rain shadow at the time of the trade winds and receives but 35% of the summer rain at Kealia and 65% of the winter rain, nevertheless the summer Kealia rainfall is but 35.5% of the total in marked contrast to the distribution on Midway.

The maps based on observations made at sea and published in the "Atlas of climatic charts of the oceans" (McDonald, 1938) indicate that from March to November less than 5% of the observations at Greenwich Mean noon made in the region record steady rain, but that from December to February 5% to 10% of such observations record steady rain in the vicinity of the eastern islands of Necker and Nihoa. Passing showers are recorded in 5% to 10% of the observations made in the vicinity of all islands from June to November, but only in the vicinity of the eastern islands is this frequency reached in the other months. The maps for all forms of precipitation (passing showers, drizzle, rain) again indicate a greater frequency of winter rain in the vicinity of Necker and Nihoa, as in the main archipelago, than around the western islands of the Leeward chain. The maps for all forms of precipitation, however, indicate an increase in rainfall in summer in the western part of the chain. It is reasonable to conclude that on none of the Leeward Islands is the rainfall likely to exceed 1100 mm., and that it is probably somewhat seasonal, with a winter wet season, on Necker and Nihoa. As Palmer (1927) indicates, the vegetation of Nihoa suggests a greater rainfall than on Necker. It is also not impossible that both Laysan Island and

Midway Island are rather wetter than Lisiansky Island.

The data given for the mean air temperature and the depression of the wet-bulb thermometer (McDonald, 1938) suggest a mean relative humidity of between 80% and 86% throughout the area.

ORNITHOLOGY

The guano birds of the Hawaiian Leeward Islands are, with the magnificent addition of two species of albatross, in general comparable to those of the Phoenix and Line Islands. The available information is derived from the works of Schauinsland (1899), Rothschild (1893-1900), Fisher (1903), Dill (1912), and Wetmore (1925b), together with some notes by Galtsoff (1933). Practically all Elschner's (1915) ornithology seems to have been derived from Schauinsland and from Fisher.

The differences that can be observed in the avifaunas of the different islands are apparently largely due to geomorphology. *Sula leucogaster plotus*¹ and *Procelsterna cerulea saxatilis* breed only on the rocky eastern islands Nihoa and Necker and the volcanic rock La Perousse, in French Frigate Shoals. The Sulidae in general appear to be abundant only on Nihoa which provides nesting sites on both rocks and bushes. Large colonies of *Diomedea immutabilis* Rothschild occur mainly where there are extensive flat areas, as on Laysan and Lisiansky Islands.

As well as considerable differences due to geomorphology and vegetation cover, there was, at least on Laysan in its original state, a marked ecological stratification, burrowing species nesting under ground breeders, and these in their turn under bush-nesting species. A temporal ecological separation also appeared to exist. Schauinsland concluded that Laysan could not have supported its enormous colony if all species had been breeding at the same time. *Diomedea immutabilis* lays in November and incubates until February (Fisher, 1903). *D. nigripes* also breeds very early in the year, and *Pterodroma leucoptera hypoleuca* (Salvin) is likewise a winter breeder. The terns on the other hand occupy their breeding grounds in the late spring and

¹ The subspecific names in general follow the distributions given by Peters (1931, *et seq.*), but there is evidently a need for revision in some genera.

early summer.

As elsewhere the ground-nesting species are probably the most important guano birds. *Sterna fuscata oahuensis* is doubtless the most abundant bird of the region. *S. lunata* appears originally to have occupied a more peripheral breeding zone on Laysan and to have been considerably less abundant than the sooty tern. *Anous stolidus pileatus* as elsewhere may breed either on the ground or in bushes, while *Gygis alba candida* lays its eggs either on rocks or on branches of bushes or small trees. Neither species is abundant enough to be of much importance as a guano producer.

Though probably exceeded in numbers by the sooty tern, *Diomedea immutabilis* must originally have greatly surpassed any other species on Laysan in biomass. The colony, prior to raids by plume hunters in 1909, probably consisted of over half a million birds; much higher estimates have in fact been given (cf. Dill, 1912). Such a number would be the metabolic equivalent of several million terns. It is, however, probable that the albatross is not quite so effective per unit mass as a phosphatizing agent, because the young are fed primarily on squids rather than fish. The two species, *D. immutabilis* and *D. nigripes*, occupy rather different nesting sites, the latter preferring a peripheral position, at least on Laysan (fig. 55).

Of the other species of the region, *Sula leucogaster plotus*, *Sula dactylatra personata*, *Phaeton rubricauda*, and frequently *Puffinus nativitatis* nest directly on the ground, though the last named may make a slight burrow.

The chief species nesting in bushes is *Anous minutus melanogenys* G. R. Gray (= *Megalopterus* or *Micranous hawaiiensis* auctt.), though as elsewhere the common noddy often builds in the same sort of environment. Dill indicates that on Laysan *Fregata minor palmerstoni* Gmelin nests on the tops of low bushes. *Sula s. rubripes*, as elsewhere, has the same habit.

Of the burrowing species *Pterodroma leucophaea hypoleuca* and *Puffinus pacificus cuneatus* are certainly the most important, though *Bulweria bulweri* (Jardine and Selby) and one or two rarer species also occur.

It is evident, not merely from qualitative accounts but also from Dill's census on Lay-

san given below and representing a period shortly after depredations by plume hunters, that at least some of the Hawaiian Leeward Islands support populations that compare well with the maximal populations found in other parts of the world.

The terrestrial biota of the Hawaiian Leeward Islands is in general a very impoverished representative of that of the main archipelago. Several endemic land plants occurred on Laysan but have apparently largely been exterminated by rabbits (Christophersen and Caum, 1931). A small number of endemic insects, of Hawaiian affinities, have been taken, mainly on Laysan and Nihoa, but on the former island most are probably now extinct owing to the destruction of their food plants. The most interesting members of the terrestrial fauna are the birds. Nihoa not only has a drepanid, *Telespiza ultima* Bryan, but also a warbler, *Conopoderas kingi* Wetmore. Laysan had representatives of both these genera, namely, *Telespiza cantans* Wilson and *Conopoderas familiaris* (Rothschild), and another drepanid, *Himatione freethi* Rothschild. Of these, *T. cantans* alone survives (Wetmore, 1924; Fisher and Baldwin, 1946). *Anas platyrhynchos laysanensis* Rothschild, the almost extinct Laysan teal, frequented a small fresh-water pond, now covered with sand, but it still may survive on the lagoon. The most interesting land bird is, however, the now extinct *Porzanula palmeri* Frowhawk, the flightless Laysan rail, which was successfully introduced onto Midway but became extinct there apparently in 1944 owing to the accidental introduction of rats (Fisher and Baldwin, 1946). This rail is generically well separated from the extinct Hawaiian rails of the genus *Pennula*. The general differentiation, particularly of the Laysan fauna, suggests a fair antiquity for the islands in their present physiographic state. Too much emphasis, however, must not be placed on the existence of the endemic genus *Porzanula* as an indication of antiquity, for the catalogue of the Rallidae is a pathetic cemetery filled with crosses commemorating flightless forms that have developed in different directions, considered of generic value, on oceanic islands, only to become extinct with the advent of modern man and his inevitable companions.

DESCRIPTION OF THE ISLANDS AND THEIR GUANO DEPOSITS

Guano appears to have been exported from the Hawaiian Islands for the first time in 1853; from 1855 to 1861 the islands are given as a source in the Annual Report on Trade and Navigation of the United States Bureau of Statistics, and an occasional cargo was recorded during subsequent years. The total quantity received in the United States between 1853 and 1893 aggregates only 5622 tons. The price varied enormously, i.e., 903 tons imported in 1857 was valued at \$1.36 per ton, while five tons imported in 1875 realized \$40.20 per ton. Obviously the imports ranged from the poorest old phosphatic material to new nitrogenous guano.

KAULA

LATITUDE 21° 38' N., LONGITUDE 160° 33' W.

A small crescentic island 168 meters high, composed of eruptive material, mainly a light brownish gray tuff. It lies southwest of the inhabited island of Niihau in the main Hawaiian Archipelago and does not really belong in the Leeward chain, though in form, size, and inaccessibility it is comparable to Nihoa. There is evidence of two cycles of volcanic activity with the incorporation of limestone fragments from an early reef in the volcanic tuff formed during the second eruptive period (Palmer, 1927).

The only indication of guano or of phosphatization is a statement by Palmer that "Mr. Edgecomb collected also a very small amount of a colorless transparent mineral, having one good cleavage, conchoidal cross-fracture, and about the same hardness as feldspar. Chemical tests show it to contain phosphoric acid, which undoubtedly originated from guano."

NIHOA, BIRD ISLAND, MOKU MANU OR MODU MANU

LATITUDE 23° 03' N., LONGITUDE 161° 55' W.

A mass of volcanic rock about 1.2 kilometers long, rising to a maximum height of 277 meters. Palmer (1927) and from him Christophersen and Caum (1931) give a good map. Elschner (1915) believed that there were a number of raised strand lines, some of them being tilted. Palmer, however, states

that most of the terraces observed by Elschner are structural, due to weathering along weak zones in the lava. A genuine and well-defined, sea-cut bench does, however, exist at an elevation of 1.5 to 2.5 meters (4–8 feet) above the present beach and is marked by caves. Considerable cave formation and undercutting are occurring along the present shore line. The island is well vegetated, grasses predominating on the ridges, while the valley bottoms are covered with a dense scrub of *Sida fallax* and *Chenopodium sandwicheum* Moquin. Two valleys contain groves of the endemic palm, *Pritchardia remota* Baccari. Several endemic herbaceous plants are also known; the whole vascular flora comprises 20 species (Christophersen and Caum, 1931). Nihoa has a fairly rich lichen flora, including a number of species not known elsewhere; Magnusson (1942), who described these lichens, characterizes the flora as nitrophilous, as would be expected on a bird island.

From the information summarized by Fisher (1903) it would appear that *Sterna fuscata oahuensis* and three species of *Sula* are the most abundant sea birds breeding on Nihoa. No data on population size are available, but the numbers must be very great, the whole island mountain seeming alive with boobies. *Sula dactylatra personata* (sub *S. cyanops*) and *S. sula rubripes* (sub *S. piscator*) nested with *Fregata minor palmerstoni* (sub *F. aquila*) in the scrub, while *S. leucogaster plotus* (sub *S. sula*) preferred the brink of the south escarpment. *Procelsterna cerulea saxatilis* was common, breeding on rocks. Of the albatrosses, *D. nigripes* appears to have been common around the island, but *D. immutabilis* was very scarce. *Anous stolidus pileatus*, *A. minutus melanogenys*, *Gygis alba candida*, *Puffinus pacificus cuneatus*, *P. nativitatis*, *Bulweria bulweri*, and *Oceanodroma markhami tristami* Salvin [sub *O. fuliginosa*; *O. m. owstoni* (Mathews and Iredale) may be the correct name] were also observed by Fisher about the island.

In spite of the large and diversified bird colony the deposits of phosphatic guano in Nihoa appear to be negligible, a condition that may be attributed to a steep slope and no doubt a somewhat higher rainfall than on the other islands. Elschner (1915) says that

only a small deposit of guano seemed to exist and that in all probability most of the avian excreta produced was washed away. Palmer (1927) states more explicitly that small amounts of guano coat some of the cliffs but again believes that most is removed by the rain, which he estimates, from the vegetation, to amount to 510 to 710 mm. (20–30 inches) per annum. He says, however, that at the tops of the cliffs at the mouths of the central valley and the next to westernmost valley also there are "some hundreds of cubic yards" of a weakly cemented conglomerate, consisting of subangular blocks of basalt cemented together by a mixture chiefly composed of soil and guano. Both Palmer and Wetmore (1924) comment on the water, acrid with salts leached from bird droppings, that seeps down some of the valleys.

NECKER ISLAND

LATITUDE 23° 35' N., LONGITUDE 164° 42' W.

Another remnant of a volcanic cone, about the same length as Nihoa, but narrower and much lower. The maximum elevation is 84 meters, and no stream valleys are developed. Palmer (1927) gives a good map. The island is composed of flows of basalt, traversed by dykes and sills. There is a low, wave-cut terrace just above sea level, but the other terraces observed by Elschner and interpreted as strand lines are structural.

Necker Island has a far less well-developed vegetation cover than Nihoa and is almost certainly drier. Palmer thinks that the vegetation indicates a mean annual rainfall of between 510 to 635 mm. (20–25 inches). The soil is shallow, coarse, and mixed with much loose rock. Only five species of vascular plants have been collected on the island, the commonest being *Chenopodium sandwichicum* which is low and straggling, seldom over 60 cm. high. *Portulaca lutea* is common on the flat tops and small ledges of the cliffs. *Sesbania tomentosa* (Hooker and Arnott), forming low spreading plants 60 cm. high and 1.8 to 3 meters in diameter, is scattered on the flat top of the main part of the island and is much favored as a nesting site by boobies and frigate birds. Much of the surface of the island is said to be devoid of vegetation (Christophersen and Caum, 1931), and in many places a whitish or yellowish crust is present

on the soil (Elschner, 1915). Eight species of lichens are recorded (Magnusson, 1942), a much poorer flora than is developed on Nihoa.

Fisher (1903) states that *Sterna fuscata oahuensis* is the commonest sea bird breeding on Necker Island, choosing for its nesting sites the softest spots where soil has collected on shelves of rock. *S. lunata* mainly occupied hollows in the rocks of the most exposed parts of the island. *Gygis alba candida* and *Procelsterna cerulea saxatilis* likewise lay on rocky surfaces. *Puffinus pacificus cuneatus* and *Phaeton rubricauda* occupy crevices in the rocks. As has been indicated, *Sula s. rubripes* and *Fregata minor palmerstoni* nest largely on *Sesbania* bushes. *Diomedea immutabilis* formed a small colony of one or two thousand birds scattered over the top of the island, and on shelves on the cliffs around the north point. The other less abundant species recorded are the same as those around Nihoa, save that *Puffinus nativitatis* and *Oceanodroma markhami tristami* were not observed. *Diomedea nigripes* is said to be the scarcest sea bird around the island.

Though apparently never worked commercially, some guano has accumulated on Necker Island. Elschner says that deposits form where they are protected from the rain by overhanging rocks. Christophersen and Caum (1931) indicate an admixture of guano with the soil. Palmer states that the promontory to the north of the western end of the island has the largest bird colony and that the guano here has accumulated to a depth of a few inches, making a friable treacherous surface. A considerable phosphatization of the lava has also taken place (Elschner, 1915, 1922).

The result of the phosphatization is apparently to produce both ferric and aluminum phosphates, but considerably larger amounts of the latter than the former. It is rather difficult to ascertain from Elschner's account the exact condition of the material. Elschner considers that the first process involved in the production of the phosphate of Necker Island is a superficial alteration of the lava, and of olivine in the dykes. This is accompanied by an oxidation of ferrous to ferric iron. He supposes that the alteration is due largely to the effect of ammonium oxalate, derived from the uric acid of the guano,

and indicates, presumably as the result of laboratory experiments, that the lava, when exposed to an ammonium oxalate solution, decomposes superficially, forming a brownish yellow mud. The hydrates and hydrated silicates so formed are then supposed to be phosphatized by ammonium phosphate in the guano solution. Ferric phosphate, being practically insoluble, is precipitated immediately, impregnating the surface of the lava to form a reddish mineral, in which there is also present some calcium phosphate, apparently as apatite, and some silica and a little aluminum phosphate. Most of the aluminum phosphate, however, migrates a little way in solution and is deposited as a hydrated phosphate, having an agate-like appearance, in cracks and vesicles in the lava. Smooth crusts and plates of considerable thickness are also found. The agate-like appearance is due to dark bands of material said to be richer in iron than are the lighter intervening bands. This banding is interpreted as a series of Liesegang rings, formed when a slightly soluble iron salt diffuses into an aluminum phosphate gel. In some cases tubes or pseudostalactites of crystalline material penetrate the phosphatic masses, and these tubes are then surrounded with concentric dark rings. The water content of the material is said to have been variable. Greenish, hard specimens are stated to have had the composition of variscite, and though rather light in color, might possibly be used as semiprecious stones. A single analysis is given:

Al ₂ O ₃	28.55%
Fe ₂ O ₃	1.01
P ₂ O ₅	41.29
H ₂ O	26.10
Indet.	3.05

In a later paper (Elschner, 1922) the analyzed material was considered different enough from variscite in composition to justify the new mineral name *myersite*. Elschner was not able to make any accurate estimates of the total amount of the phosphate present on the island, but considered that it might bear thousands of tons. It is extremely difficult to ascertain from his account how much of his conclusions were based on observation and analysis, and how much depended on more or less probable suppositions. Palmer (1927) describes the oc-

currence briefly, as of an agate-like phosphate in veins filling joints in the volcanic rock, the purer material being nearly white, the iron-stained bands brown.

In addition to these phosphate minerals, gypsum stalactites are found in the cavities that have formed in the weak upper surfaces of lava flows. The sulphur in the gypsum is supposed by Elschner to be derived from guano, but Palmer thinks that the source of the sulphate is sea spray. These gypsum stalactites are said by Elschner to be very impure, containing up to 13% glauberite, Na₂SO₄. Calcium and magnesium carbonates, acid insoluble matter, calcium diphosphate and calcium triphosphate, and small glittering crystals of struvite also appear to be associated with the gypsum. Struvite, with ammonium phosphate, is apparently also recognizable in the cakes of dry guano that may be found on the coral sand thrown up on the terraces around the island. Partial phosphatization of this sand has occurred, forming a peculiar porous conglomerate in which both calcium diphosphate and calcium triphosphate are supposed to exist.

Though there are no streams or even stream valleys on the island, several seeps are noted by Palmer, the water of these helocrene springs being acrid, as on Nihoa.

FRENCH FRIGATE SHOALS

LATITUDE 23° 46' N., LONGITUDE 166° 16' W.

An imperfect, crescent-shaped atoll, with a number of sandy islands, partially surrounding two rocks, the larger one, La Perousse, being 150 meters long and 37 meters high. The number of sandy islets on the atoll rim is variously given and is evidently inconsistent. Fisher (1903) speaks of four islets covered with vegetation. Elschner (1915) says that in 1912 and 1913 there were five islets, and in 1914 nine, but of these only four were vegetated and permanent. Palmer (1927) and, on his authority, Christophersen and Caum, mention 16 islets in 1923, of which nine had vegetation. Palmer says that these did not correspond to the five islets on the United States Hydrographic Office chart made in 1859 and that destruction and building must be occurring continually. *Boerhaavia diffusa* and *Portulaca lutea* appear to be the commonest plants on the vegetated islands.

From Fisher's (1903) list it appears that *Sterna fuscata oahuensis*, *S. lunata*, *Gygis alba candida*, *Anous stolidus pileatus*, *Procelsterna cerulea saxatilis*, *Diomedea immutabilis*, *D. nigripes*, *Puffinus nativitatis*, *Sula dactylatra personata*, *S. s. rubripes*, *S. leucogaster plotus*, and *Fregata minor palmerstoni* have been observed frequenting the atoll, but there is little information about their ecology save that the terns swarmed over the largest sandy islet, and that birds were very abundant on La Perousse rock where *P. c. saxatilis* presumably breeds.

Heiden (1887) records the islands of French Frigate Shoals as a source of guano. Elschner (1913) states that 20 men from the ship "Gembria" were left on the islands in 1859 to collect seal skins, fish oil, shark fins, and guano. Bryan (1926) remarks that La Perousse is covered with guano. The rather large import from the Sandwich Islands (United States Bureau of Statistics, Annual Report in Commerce and Navigation) for 1859, namely, 1671 tons against 75 tons in the previous year and 650 tons in the subsequent year, may be the result of the visit of the "Gembria." No analyses appear to be available.

GARDNER ISLAND

LATITUDE 25° 00' N., LONGITUDE 168° 00' W.

A volcanic pinnacle of basalt, 58 meters high, with a smaller rock to the northwest. Landings can be made in comparatively smooth weather. According to the United States Coast Pilot ("The Hawaiian Islands," second edition, United States Coast and Geodetic Survey, 1933) the rock is covered with guano and has the appearance of being capped with snow. Palmer (1927) says that Dr. S. C. Ball collected light-colored or colorless phosphatic material forming veins in cracks in the rocks, and that in places he found that the phosphate forms a crust of delicate acicular crystals.

MARO AND DOWSETT REEF

LATITUDE 20° 25' N., LONGITUDE 170° 35' W.

A large coral bank with a single small emergent rock about 60 cm. above high water. Heiden (1887) records guano from Maro Reef, but unless there was formerly more land surface exposed the record is obviously very doubtful.

LAYSAN

LATITUDE 25° 46' N., LONGITUDE 171° 44' W.

A slightly elevated atoll, with no visible trace of a volcanic foundation. The island is 3 kilometers long and about 1.6 wide and contains a completely closed lagoon containing very salt water. A small fresh-water pond now filled with sand formerly existed. There is a wide bank about 14 miles in diameter around the island on which depths up to 37 meters are recorded. In its original condition prior to the introduction of rabbits, Laysan must have been a veritable *Paradisus terrestris*. Fortunately, admirable descriptions by Schauinsland and by Fisher exist, for later the island became a sandy waste that has lost most of its endemic plants, birds, and insects. It has apparently now largely recovered its vegetation cover, but there is no adequate information as what species have survived.

The atoll rim rises near the north end to a height of 10.7 meters. A narrow littoral slope was covered with short grass and trailing morning glories, *Ipomaea indica* (Burmans) Merrill and *I. pes-caprae* (Linnaeus) Roth. The Laysan sandalwood, *Santalum cuneatum* var. *laysanicum* Rock, flourished along the shore. The inner slope was covered with bushy grass, *Eragrostis variabilis* (Gaudichaud) Streudel, in separate clumps, with several species of shrub, *Chenopodium sandwicheum* being the most important. Near the lagoon there was a ring of *Cyperus* and within this the reddish purple *Sesuvium portulacastrum* and yellow *Portulaca lutea*, a favorite haunt of the Laysan honeyeater, *Himatione freethi*. The terrain immediately surrounding the lagoon was covered with thin chips of phosphate rock. A small pond existed to the south of the lagoon. A palm, probably an endemic *Pritchardia*, existed until 1891 but became extinct for unknown reasons before 1900; no specimens exist. Twenty-six species of vascular plants are known to have inhabited the island. In 1923 only small patches of *Sesuvium*, *Portulaca*, and *Scaevola frutescens* (Miller) Krause, small seedlings of *Ipomaea pes-caprae*, and buried stumps, attempting to sprout, of *Santalum*, represented the whole vascular flora (Christophersen and Caum, 1931).

Apart from the land birds, of which *Cono-*

poderas familiaris, *Himatione freethi*, and *Porzanula palmeri* are now extinct, the breeding avifauna consists of 16 species, the numbers present in 1911 being estimated by Dill as follows:

<i>Sterna fuscata oahuensis</i>	333,900
<i>S. lunata</i>	50,000
<i>Anous stolidus</i>	5,000
<i>A. m. melanogenys</i>	3,000
<i>Gygis alba candida</i>	75
<i>Diomedea immutabilis</i>	180,000
<i>D. nigripes</i>	85,000
<i>Puffinus pacificus cuneatus</i>	100,000
<i>P. nativitatis</i>	75,000
<i>P. hypoleuca</i>	160,000
<i>Bulweria bulweri</i>	1,000
<i>Oceanodroma markhami owstoni</i> (sub <i>tristami</i>)	3
<i>Phaeton rubricauda</i>	300
<i>Sula dactylatra personata</i>	65
<i>S. sula rubripes</i>	125
<i>Fregata minor palmerstoni</i>	12,500

The disposition of the nesting sites is given in figure 55, redrawn from Dill's map. The *D. immutabilis* colony had a much greater extent prior to 1909 than in 1911. The positions of the main guano patches indicated by Elschner (1915) are also shown in the figure. When it is remembered that Dill's map is based on a reduced population the distribution strongly suggests that most of the material was derived from *D. immutabilis* and *S. fuscata oahuensis*.

Elschner gives an analysis of more or less nitrogenous guano from a frigate bird's nest on Laysan, the sample consisting of a mixture of quite fresh excreta and older material that had been leached by rain. The composition is similar to nitrogenous Peruvian guano. He also gives the following analysis of the best brown phosphates:

H ₂ O	7.16%
Total nitrogen	0.68
CaO	46.63
MgO	0.37
(Al,Fe)PO ₄	0.36
P ₂ O ₅	41.13
CO ₂	1.14
SO ₃	0.74
F	strong traces

Assuming that the carbonate and sulphate are present as calcium salts and the magne-

sium as triphosphate, the corrected molecular ratio CaO:P₂O₅ is 1:0.359, implying a considerable amount of phosphate less basic than Ca₃P₂O₈. Elschner assumes 69.70% of the latter and 16.75% CaHPO₄; if an apatite-like material be the major constituent the amount of CaHPO₄ will be greater. At the

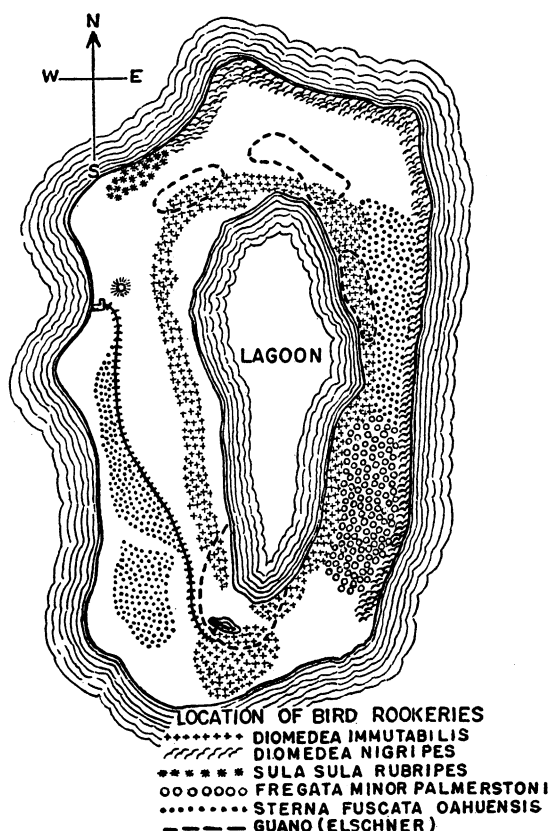


FIG. 55. Map of Laysan showing bird colonies. After Dill.

time of Elschner's visit little such high grade material remained. He states, however, that the whole depression around the lagoon and the floor of the same are penetrated with horizontal bands of brown phosphate between white unphosphatized carbonate. Phosphatized coral sand, consisting of oolitic grains, phosphatized on the outside but with carbonate centers occurred, and frequently a fine brown powder, completely phosphatized ("alluvial phosphate" of the Pacific phos-

phate diggers) occurred. The brown color of these materials faded on exposure to the sun.

LISIANSKY ISLAND

LATITUDE 26° 02' N., LONGITUDE 173° 59' W.

An elevated atoll with a completely dry central depression. The island is about 2 kilometers long and 1.2 kilometers wide with crescentic ridges of sand at its north and south ends enclosing the lagoon area. The highest part of the northern ridge is an elevation of 13.4 meters. The island is surrounded by a large reef platform.

The original vegetation of the island is uncertain; the older accounts have been summarized by Christophersen and Caum (1931) and by Bryan (1942). Grass and scrub covered the island. Prior to 1915 rabbits were introduced and by Elschner's visit had eaten virtually the entire vegetation of the island save some introduced tobacco plants and a few specimens of *Ipomaea*. By 1923 the rabbits had all died, and a patch of the grass *Eragrostis variabilis* had established itself along with rarer specimens of *Sesuvium portulacastrum*, *Portulaca* sp., and *Nama sandwicensis* var. *laysanicum* A. Brome. In contrast to the remarkable original avifauna on Laysan, Lisiansky even in its virgin state seems to have lacked resident land birds, except a rail which became extinct before the island was studied scientifically.

Walker (1909) estimated that in 1891 a thousand tons of guano were present in the lagoon area. The island was leased to the North Pacific Phosphate and Fertilizer Company in March, 1890. Elschner says that only the best phosphate was shipped and that the whole surface of the island is partially phosphatized, all the sand grains being coated with a more or less fine film of phosphate. He gives phosphate determinations (as $\text{Ca}_3\text{P}_2\text{O}_8$ in original) as follows:

Surface sand	0.99%, 2.41%
In cavities	1.46%, 4.19%, 0.97%, 5.10%
Surface sand	
near lagoon	6.54%, 17.85%, 28.47%, 11.04%

The imports of guano from the Hawaiian Islands into the United States for 1892 and 1893 are given as 229 tons, valued at \$23 per ton. This material may be the high grade

phosphate from Lisiansky Island but doubtless does not include the entire yield of the island.

MIDWAY ISLAND

LATITUDE 28° 13' N., LONGITUDE 177° 23' W.

A circular atoll with two main islets, Sand and Eastern or Green, on the southern part of the rim. It is well known for its strategic and commercial importance. Sand Islet, 13.1 meters high, is now well planted but consisted originally of bare sand with little vegetation, while Eastern Islet had more original plant cover. Christophersen and Caum record 19 species of vascular plants that may reasonably be regarded as indigenous. The commonest birds (Bryan, 1906) originally appear to have been *Sierna fuscata oahuensis* and *Diomedea nigripes*, the latter being three times as numerous as *D. immutabilis*. The albatross colonies suffered badly from Japanese plume hunters early in the present century. *Puffinus pacificus cuneatus* bred on Eastern Island which was honeycombed with its burrows; *Fregata minor palmerstoni* had a colony on the same island. A few *Anous stolidus*, *A. minutus melanogenys*, *Gygis alba candida*, *Phaeton rubricauda*, *Sula sula rubripes*, and *S. dactylatra personata* were also observed by Bryan. A modern census indicating that sooty terns, the two albatrosses, and wedge-tailed shearwaters are still the commonest birds on Sand Island and the three last-named species the commonest on Eastern Island is given by Fisher and Baldwin (1946).

The only indications of phosphatization are, first, a statement of Elschner that some phosphate covered by sand exists on Sand Island, and, second, Bryan's (1906) remark that the soil in the interior of Eastern Island is coral sand mixed to some extent with vegetable mold and guano. The small deposits are probably very impure, and no exploitation seems to have taken place.

The remaining reefs of the Hawaiian Leeward group with emergent land, namely, Pearl and Hermes Reef (latitude 27° 48' N., longitude 175° 51' W.) and Kure or Ocean Island (latitude 28° 25' N., longitude 178° 25' W., not to be confused with Banaba or Ocean Island) do not appear to have borne any phosphatic deposits.

RAISED PHOSPHATIZED ATOLLS IN THE TUAMOTU GROUP AND ELSEWHERE IN THE SOUTH PACIFIC

Peripheral to the region that has just been considered are two groups of phosphate islands of great commercial importance. One group, consisting of Makatea and probably some other islands in the Tuamotu Archipelago, lies to the southeast. The other group of two islands, Nauru or Pleasant Island and Banaba or Ocean Island, lies to the west of the Gilbert Islands and westward of the region that has just been considered. Nauru, Makatea, and Ocean Islands are very clearly distinguished from the localities in the central Pacific that have been previously discussed in having undergone strong local elevation, probably in all cases more than once, prior to the deposition of the guano from which the phosphate is derived. Similar characters are exhibited by certain phosphate islands in the western Pacific, but the hydrographic and climatic problems involved in any interpretation are here more complex than in the central Pacific. It is therefore convenient to treat the two groups of the central region first, beginning with the southeastern group.

Three islands at the western end of the Tuamotu (or Paumotu) group and one to the far east of the archipelago appear to have deposits of phosphate. The most important of these islands is Makatea, which bears an important phosphate deposit comparable to those of Ocean Island and Nauru. The adjacent and much less strikingly elevated Niau and Matahiva are also reported to bear small quantities of phosphate. To the east of the Tuamotu Archipelago, Henderson, or Elizabeth, Island is a well-elevated atoll with a deposit doubtfully said to be greater than that on Niau and Matahiva, but of no commercial importance and of negligible extent compared to that of Makatea. Mauke in the Cook Islands and Niue, or Savage, Island, east of the Tonga group, much farther west but in about the same latitude, also bore some phosphate. It is not impossible that, so far as the nature of their phosphate deposits is concerned, Flint and Caroline Islands belong with the lower of the elevated islands discussed in this section rather than with the Line Islands.

NIUE OR SAVAGE ISLAND

LATITUDE $19^{\circ} 02' \text{ S.}$, LONGITUDE $169^{\circ} 54' \text{ W.}$

The westernmost of the Cook Islands, described as having jagged coral rock covered with impenetrable scrub, belts of heavy timber, and coconut groves. The residual soil is very fertile (Becke, 1897). Power (1905) indicates that phosphate has been found but not in commercially significant quantities.

MAUKE, MAUKI, OR MAUTI ISLAND

LATITUDE $20^{\circ} 08' \text{ S.}$, LONGITUDE $157^{\circ} 23' \text{ W.}$

The easternmost of the Cook Islands, apparently a somewhat elevated atoll, clearly not more than 30 meters high, for the "Pacific islands pilot" (United States Hydrographic Office, 1916b) indicates that the tops of trees growing upon it reach 120 feet above sea level. It is apparently well vegetated. The only evidence of phosphatization is in a statement given in Lord Byron's (1826) voyage of H.M.S. "Blonde." On the return voyage, after conveying the body of King Kamehameha II and his queen from England to Hawaii, Byron's officers examined Mauke. The island is said to have been of coral formation but this is followed by the remark, "We brought away two or three specimens of phosphate of lime" (p. 214). Nothing more has been written about the occurrence, but as it was known to Dana (1852) it is probable that later explorers also knew of it and found nothing worth exploiting.

MAKATEA

LATITUDE $15^{\circ} 50' \text{ S.}$, LONGITUDE $148^{\circ} 13' \text{ W.}$

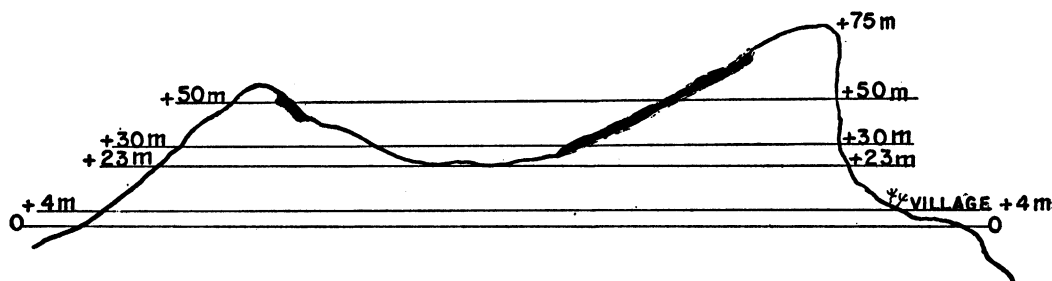
An elevated coral island on the western edge of the Tuamotu Archipelago. It has been described by a number of investigators; the account given below is based primarily on the descriptions by Agassiz (1903), Elschner (1913), and Wilder (1934). Some additional information on the phosphate deposits, probably derived from notes accompanying specimens, is also given by Stutzer (1932).

Makatea is a kidney-shaped island, its concave side facing northeast. Its total length

appears from the official map of La Compagnie Française des Phosphates de l'Océanie, reproduced by Wilder, to be 8 kilometers. The highest point on the island, a hill named Putiare, has, according to the same authority, an altitude of 113 meters; all other authorities give lower elevations. There is a narrow fringing reef, up to 150 meters in width, around the island. Along the northeast and western coasts the coral shore is continuous with a wide beach which extends to an elevation of up to 15 meters. This beach presumably was formed when the ocean around the island stood at a slightly higher level than it

the establishment of the lines of caverns, which indicate rather temporary stages in elevation. There is therefore reason to suppose that the island has undergone two elevations with a period of subsidence between them. Elschner gives the altitudes of the three more elevated strand lines as 23, 30, and 50 meters. Agassiz indicates altitudes of 7 to 8 meters (20–25 feet) and about 10 meters (30 feet) for the two lower terraces, which are best developed in the southern part of the island. Elschner's two lower terraces apparently comprise one at 4 meters and the modern beach. The central part of the island

MAKATEA



HORIZONTAL SCALE 1:37500
VERTICAL SCALE 1:3000

— PHOSPHATE DEPOSIT
HORIZONTAL LINES GIVE ANCIENT SEA LEVELS
ACCORDING TO ELSCHNER

FIG. 56. Section through Makatea. After Elschner.

does today; on it the village and port of Ternas are built. Agassiz says that it is part of the base of the first of the terraces, marking numerous strand lines, that can be identified around the island, planed down to the low-water mark and deeply pitted and honey-combed. Within the littoral plateau the island rises abruptly. The cliffs within the coastal area are best developed in the northern part of the island and according to Agassiz bear rows of caverns marking five periods of elevation. Some of these beach levels can be traced along the eastern face of the island. Davis points out that the cliff itself must have been formed by cutting at its base prior to

forms a shallow basin, its lowest part 35 meters above sea level according to Stutzer, though indicated at less than 23 meters above sea level on Elschner's section (fig. 56). Agassiz regarded this depression as a sink due to solution of the limestone; all other authors consider it to have been originally a lagoon. The entire interior of the island, where not covered with phosphate, is greatly dissected into pinnacles.

At the present time Makatea has a rich vegetation (Wilder). A number of Polynesian cultivated plants have been introduced, and more recently adventive and ornamental plants of various origins have become wild.

The interior of the island, where undisturbed, is, however, covered with a fairly rich tropical forest. A single species of plant, the palm *Eupritchardia vuylstekeanum* (H. Wendland) O. Kuntze, is endemic, occurring only in a part of the central basis of the island.

Makatea possesses a small terrestrial avifauna, including the pigeons *Ducula aurorae* (Peale), also known from Tahiti, and *Phalacrocorax purpuratus calcurus* (G. R. Gray), an endemic subspecies of a widespread species represented by *P. p. coralensis* (Peale) on most of the other islands in the Tuamotu Archipelago. There is also a rather well-differentiated subspecies of warbler, *Conopodas atypha erema* Townsend and Wetmore, on Makatea. A few other islands have endemic subspecies of *C. atypha*, but *erema* appears to be better defined than most of the other Tuamotu races (Townsend and Wetmore, 1919; Murphy and Mathews, 1929). The existence of an endemic palm and rather more or better defined endemic races of birds than occur on the other islands suggests a fair antiquity for the land surface in its present ecological state. The molluscan fauna, however, appears to be poor and gives little evidence of endemism (Cooke, 1934). The sea birds frequenting Makatea are briefly listed by Wilder who records *Sula sula rubripes* (sub *piscator*), *Anous stolidus* (sub *Stolidas stolidas* [sic]), *A. minutus* (sub *stolidas hawaiiensis*), and *Gygis alba* (sub *G. a. kittlitzii*), all of which were common about the shores, while *Phaeton lepturus* was seen nesting on high cliffs.

Apart from the phosphate deposit, Makatea is composed entirely of coral rock. Agassiz states that he collected, on the west face of the island, from the first and second terraces, fossils similar in every respect to those from Fiji which have been "determined by Mr. Dall and myself as tertiary. We also collected many fossils on our way across the island, principally in the deep cuts and caverns of the vertical cliffs on both faces of the island." If the comparison with Fiji is correct, a Miocene age is probable (Ladd and Hoffmeister, 1945). No further report on this material ever seems to have been made.¹ In

¹ Inquiry of Dr. Henry Stetson elicits the information that this collection is not now known to exist at Harvard.

view of Agassiz's remarks on the smallness of the corals of the Tuamotus in general, and of his finding "Corals, mainly small heads of Madreporae, Pavonia and Porites, . . . in great abundance on the slope" around Makatea down "to eight fathoms" it would be particularly interesting to know if fossil corals from the reef rock were somewhat reduced specimens.

Apart from this unsatisfactory record, the only other published paleontological information is Wilder's statement that "remains of a prehistoric reptile in the phosphate deposits indicate a very remote period of uplift." This statement appears so improbable that it can hardly be taken very seriously in the absence of further information. It may well be based on verbal communication from the officials of the phosphate company and could conceivably refer to the remains of a turtle, to *Carcharodon* teeth, or to some concretion not of vertebrate origin.

The coral rock of Makatea, as that of certain other elevated phosphatic islands (Nauru, Ocean Island, and Christmas Island, Indian Ocean) is dolomatized. Silliman found little magnesium in fresh coral from the island, but 38.07% $MgCO_3$ in the consolidated rock collected by Dana (1852). T. S. Hunt (1855) likewise found, in the same material, 38.77% and 38.25% $MgCO_3$. Another sample analyzed by Silliman contained much less magnesium carbonate, namely, 5.29%.

The phosphate deposits of Makatea are found within the central depression, mainly on its northern flanks. The phosphate fills the pockets between the pinnacles of the Karrenfeld, which, though less developed than on Ocean Island and Nauru, is nevertheless very striking, and is beautifully shown in photographs (pl. 14, fig. 2) of parts of the field that have recently been worked out (Elschner, 1913), as the material is softer than that found on Ocean Island and Nauru and consists mainly of yellow phosphatized coral sand or gravel with larger lumps embedded therein. Much has an oolitic structure. Stutzer says that in the region of the strand lines of the lagoon corresponding to the higher sea levels the phosphate forms here and there banded layers. Such banded phosphate is found occasionally between loose phosphate. The boundary between

phosphate and dolomite is clearly sharp. Noyes (1944) gives the total reserve as 10,000,000 tons. Aso (1940), however, indicates this to have been the original estimate and that later 30,000,000 tons of phosphate were believed to be present.

It would appear from the diagram given by Elschner that the lower edge of the main deposit lies just below the level of the 30-meter strand line and more than half the deposit lies below the 50-meter strand line. The main part of the bird colony responsible for the phosphatization presumably occupied

contain 37% to 39% P_2O_5 , though some poorer phosphatic sand containing but 33% P_2O_5 was found by Elschner nearer to the shore than the main deposit. Elschner found very little fluorine in the material that he examined, but this may be an analytical error. The best determinations give a very high fluorine content. In view of the divergence in these fluorine determinations it is unfortunate that nothing is known as to the exact position from which analyzed material was obtained. The following analyses have been published:

	ANALYSIS IN PARIS FOR ELSCHNER (1913)	ELSCHNER (1913) ANALYSIS	OGSTON AND MOORE (in STUTZER, 1932) (DRIED AT 100°C.)
H ₂ O at 100°C.	1.40%	—	—
Ign. loss	3.05	2.90%	3.24% (organic matter and bound H ₂ O)
Insol.	0.08	0.12	0.12 (siliceous)
P ₂ O ₅	37.88	38.68	38.35
CaO	53.70	53.58	51.82
CO ₂	2.55	2.68	2.55
(Al,Fe) ₂ O ₃	0.40	0.62	0.92
N	tr.	—	—
MgO	—	0.12	—
SO ₄	—	0.14	0.14
F	—	very little	1.30
Indet.	0.94	1.16	1.56 (incl. MgO)

the eastern shore of the lagoon under the lee of the eastern wall of the island and moved down deeper into the depression as the sea level fell and suitable breeding sites were progressively exposed. If Stutzer's account of banded phosphate corresponding to stationary water levels is correct, it is not clear why there was no phosphate deposition from the lagoon water in the other parts of the depression, notably at the deepest point. It is obvious that the material could not have remained *in situ* on the lagoon slope if the rainfall had been great. The fact that the upper deposits are not apparently much thicker than the lower suggests that the upper boundary of the colony moved down, conceivably owing to establishment of vegetation, so that the lagoon shore was occupied by a colony of about the same width but at a progressively lower level. A lower rainfall than there is today, but not excessive aridity, may perhaps be postulated at the time of phosphate formation.

The best grades of Makatea phosphate

Two fluorine determinations by Jacob, Hill, Marshall, and Reynolds (1933) give 3.25% and 3.42%, respectively. The P_2O_5 contents are 38.22% and 37.94%, and the ratios F: P_2O_5 are 0.085 and 0.090. These ratios are the highest recorded for insular phosphate.

NIAU

LATITUDE 16° 10' S., LONGITUDE 146° 20' W.

A slightly elevated atoll, about 6.5 kilometers in diameter with a lagoon superficially completely cut off from the sea, though there may be subterranean connections. The maximum altitude of the island appears to be about 8 meters. At rare intervals, during hurricanes, sea water may be carried over the rim into the lagoon (Agassiz, 1903). The water in the latter was found by Agassiz to have a density of 1.0216 at 28° C. Large mullet and diminutive specimens of various mollusks were found living in this water. Agassiz states that the land rim is composed of old coral limestone "pitted and honey-combed

and covered with diminutive spires and points, as is all the old ledge rock of Makatea; in fact it was like it in all respects, full of tertiary fossils." This old rock is said to be covered in places by a conglomerate composed of beach rock, broken coral, and pieces of the old limestone, cemented together. Agassiz says that "this conglomerate or beach rock has also comparatively recently been elevated to a height of from six to eight feet above high water mark." In its present state the island is apparently richly vegetated. A supposedly endemic subspecies of kingfisher, *Halcyon gambieri gertrudae* Murphy, and a well-developed endemic subspecies of *Conopoderas*, *C. atypha niauensis* Murphy and Mathews, inhabit the island.

The only evidence of phosphatization is a statement of Privat-Deschanel (1910) that a small amount of phosphate has been found on Niau. It may well constitute the cement of the conglomerate mentioned by Agassiz. Privat-Deschanel was apparently in touch with French commercial concerns interested in phosphates, and his statement is probably reliable. The statement is repeated by Elschner and Stutzer, doubtless from Privat-Deschanel's paper.

MATAHIVA OR LAZAREFF ISLAND

LATITUDE 14° 54' S., LONGITUDE 148° 42' W.

The most western island of the Tuamotu Archipelago, said by the "Pacific islands pilot" to be a well-wooded atoll about 8 kilometers in diameter with a single passage into its lagoon. Agassiz, who apparently did not land, concluded that the tops of the highest rocks of the land rim lay at 3.0 to 3.7 meters above the sea. These rocks were identified by him as "old ledge rock," i.e., the supposedly Tertiary coral limestone that forms Makatea and Niau. Davis states that only Rangiroa and perhaps Apatahi and Kanehi of the unphosphatized members of the Tuamotu Archipelago have old rock as elevated as that on Matahiva. The land fauna appears to be identical with that of adjacent islands; the *Conopoderas* present is *C. a. atypha*, known on 27 other islands of the group. Privat-Deschanel states that a small deposit of phosphate occurs on the island, and the statement is repeated by Stutzer.

ELIZABETH OR HENDERSON ISLAND

LATITUDE 24° 22' S., LONGITUDE 128° 19' W.

A remarkable elevated coral island about 8 kilometers long and 4 kilometers wide ("Pacific islands pilot," vol. 2). The maximum altitude appears to be about 30.5 meters. The greater part of the land surface forms a plateau surrounded by cliffs about 15 meters high. At the north end the cliff is apparently absent. Descriptions of the island are given by North (1908), Murray (quoted in Ogilvie-Grant, 1913), Beck (1921), and Murphy (1924). Photographs are given by the first and last of these authors which indicate a sloping littoral terrace along the base of the cliffs. The surface of the island is said to bear very poor and scanty soil, and the only supply of fresh water is from drippings off the roof of an almost inaccessible cave.

The "Pilot" says that two men marooned on the island survived on rain water. In spite of the poor soil the whole surface of the island is richly overgrown with trees and scrub. A few coconuts, limes, and oranges, planted on the littoral plain, are said to grow well. All descriptions indicate that the surface of the plateau is very irregular. Beck says that the hard coral rock is broken in places by sharp jagged pinnacles and that it is far more difficult to traverse than the fringing reef outside the beach. The old account by the Rev. T. B. Murray quoted by Ogilvie-Grant states that the whole surface is scattered with marine shells and pieces of coral.

The fauna of the island is little known, but there are four land birds, all endemic, namely, *Nesophylax ater* (North), a flightless rail belonging to an endemic genus, *Ptilinopus insularis* (North), *Vini stepheni* (North), and *Conopoderas vauhani taiti* (Ogilvie-Grant). There is said to be a Polynesian rat on the island, and minute terrestrial mollusks and a skink occur there.

The sea birds are listed by Ogilvie-Grant who records *Sula sula rubripes* (sub *piscator*), *Procelsterna cerulea*, *Anous minutus* (sub *leucocapillus*), and *Gygis alba candida*. *Fregata* and *Puffinus* also appear to frequent the island (North).

Henderson Island appears to be an uplifted atoll like Nauru or Makatea, but no indication of a depression corresponding to a lagoon

has been given. There is evidently some development of a Karrenfeld. The rather marked endemism of the bird fauna suggests a fair antiquity for the land surface in its present state, though the warbler is very close to the Pitcairn form. On at least three occasions Henderson Island appears to have been examined for commercially significant phosphate deposits. The British Phosphate Commissioners indicate (*in litt.*) that Mr. G. I. Ellis visited the island and obtained samples of alluvial phosphate in barren, swampy land. These were received in Melbourne May 3, 1900, and analyzed by A. E. Stephen who found:

	I (LAB. No. 137)	II (LAB. No. 139)
Moisture	18.80%	10.95%
Organic matter	37.00	26.17
CaCO ₃	9.62	45.40

Ca ₃ P ₂ O ₈	18.01	8.52
Insol.	9.23	4.25
Indet.	7.34	4.71

Specimen I is called first quality alluvial; apparently another specimen (No. 138), also so designated, was found to contain iron and alumina.

DUCIE ISLAND

LATITUDE 24° 40' S., LONGITUDE 124° 47' W.

Leased to Dr. W. L. Crowther in 1865 and examined in 1866, but there is no evidence that guano or phosphate was found. No exploitation apparently took place, but the island is marked as a guano island on Privat-Deschanel's map.

A lease of Catos Island, reported in latitude 25° 15' S., longitude 115° 34' W., was also granted to Dr. Crowther, but the island is apparently non-existent.

RAISED PHOSPHATIZED ATOLLS IN THE EQUATORIAL PACIFIC (OCEAN AND NAURU ISLANDS)

The two most important phosphatized islands in the Pacific lie close to the Equator far west of the equatorial guano islands already considered. It is possible that a third deposit in the same general region may have existed on Apaiang, Apia, or Charlotte Island (latitude 1° 49' N., longitude 172° 58' E.). Heiden, as already has been indicated, recorded a small amount of phosphate imported into Hamburg from Apia, without indicating whether Apia in Tahiti or this island is meant. The available information about the region relates solely to Ocean Island and Nauru.

Ocean Island and Nauru both lie within latitude 1° S. of the Equator between longitude 167° and longitude 170° E. They thus lie a little south of the maximum of the equatorial rain belt, but in these longitudes the wet zone extends southward, so that, according to the "Atlas of climatic charts of the oceans" (McDonald, 1938), steady rain may be expected in over 10% of the observations made at sea at Greenwich Mean noon between September and May. The months of June, July, and August appear to be drier.

The actual rainfall data (Reed, 1927) show that the annual precipitation does not differ

greatly on the two islands, Nauru having a mean annual rainfall of 2140 mm., Ocean of 2053 mm. This rainfall is, however, distributed rather differently, for February (287 mm.) appears to be the wettest month on Nauru and June (127 mm.) the driest, while on Ocean Island, January (327 mm.) is the wettest month, and August (68 mm.) the driest. Ocean thus has a more strikingly seasonal rainfall than Nauru; on the former island all months from June to November inclusive have a mean rainfall under 150 mm., on the latter this is true only of May, June, and October. The mean temperatures do not differ much from those observed at Fanning and Malden Islands in about the same latitudes farther east.

As far as can be judged from the knowledge of the large-scale circulation in the central Pacific, the hydrographic characters of the ocean around these two islands is likely to be comparable to the better known equatorial region farther eastward.

Neither Ocean Island nor Nauru is now a bird island. Power indicates that the only sea birds are a few *Gygis alba* subsp. (sub *candida*), *Anous minutus* subsp. (sub *Micranous leucocapillus*), and an occasional *Fregata*. He

supposes that the bird colonies were dispersed when the islands were first colonized by man. Hambruck indicates on Nauru *Gygis alba*, *Anous* sp., *Fregata* sp., and two species of *Sterna*, as well as various shore birds. Like Power he indicates that sea birds are not abundant. Nauru has at least one land bird, the Nauru nightingale reed warbler, *Acrocephalus lusciniæ rehsei*. Finsch and Hambruck also implied the existence of a sunbird and a flycatcher of the genus *Rhipidura*. Mayr (1945) mentions no land bird from Nauru save the warbler.

BANABA, PANOPA, OR OCEAN ISLAND

LATITUDE 00° 53' S., LONGITUDE 169° 35' E.

An elliptical island 2780 meters long and 2200 meters wide, its major axis directed northwest-southeast, and with a shallow bay cut out of its southern shore (fig. 57). The only important accounts are by Power (1905) and by Owen (1923, 1927). There is a fringing reef, or rather a plain, of marine denudation about 100 meters wide around the island. The reef is a portion of the main island, and bases of former pinnacles and in one place a stalactite *in situ* in cave debris were observed on it by Power. This can only mean that the modern shore is cut back into the island. Power notes that the position of old native house platforms indicates that the cliffs are still being cut back into the island. The reef is broken by gullies which tend to become roofed over with recent coral, leaving blow holes at the shoreward end (Power, 1905).

Along the northwest shore there is a raised beach up to 9 meters high (Owen, 1923). Power comments on the presence of caves above sea level. In some places two caves are present, one above the other, separated by a layer of coral rock forming the roof of one and the floor of the other. The relationship of these caves to the raised beach is unknown.

Save at the south end, the whole coast of the island is formed by vertical cliffs 4 to 9 meters high. The section provided by these cliffs indicates 1.5 to 5.2 meters of fragmentary coral lying on consolidated coral rock. Power implies that such fragmented coral may cover the pinnacles of the Karrenfeld. From Owen's account it seems certain that, if this is actually the case, the fragments are phosphatized. Often a banded deposit of

CaCO₃, clearly dissolved out of the upper fragmental layer, separates the latter from the consolidated rock (Power, 1905). The phosphate capping may be 24 meters thick, though usually it is not over 15 meters thick. Under the phosphate the coral is dolomitized. Power's single analysis gave:

H ₂ O	0.111%
CaO	32.700
MgO	18.552
CO ₂	45.872
(Al,Fe) ₂ O ₃	0.380
SiO ₂	0.292
Other constituents	2.093

This corresponds to about 39% MgCO₃. Owen found from 43% to 45% MgCO₃ in the more superficial layers, but later (1927) from a deep cave recorded but 20% MgCO₃. No clear evidence of the age of the coral rock is available; Power speaks of fossils but gives no determinations. Owen says that they are so altered that determination of all but a tooth of *Carcharodon megalodon* was impossible. This tooth indicates a post-Miocene age. Power thinks that not only have the interstices in the original reef rock been filled by secondary deposition of CaCO₃ but that all the fossils are casts; he doubts that any original coral remains.

The dolomitized coral, when stripped of phosphate, is seen to be cut by at least three raised beaches, which are tilted, dipping rather less than 0° 20' south-southeast. The central part of the island, which reaches a height of 92 meters according to Owen (the "Pacific islands pilot" gives 81 meters which may be the general elevation of the interior) is relatively flat and is considered by Power to represent the site of a lagoon. The whole of the dolomite surface, wherever exposed, is dissected into pinnacles to form a Karrenfeld. Power seems to have regarded the initial stages of pinnacle formation as due to radial and concentric cracking of the uplifted island. He says that cracks can be observed in the coral rock and that they may be interrupted by fossilized coral heads. He attributes the later stages in pinnacle formation to marine erosion.

The tops of pinnacles appear to be exposed where the central plateau slopes down towards the cliffs. Power indicates that broken coral debris lies over them, but it is not clear

from his account, though virtually certain from that of Owen, that this debris is phosphatized. Power argues in favor of marine erosion as the significant agent in the formation of the pinnacles because the coral rock of the pinnacles is not pitted and has vertical

is clearly analogous to the Ocean Island Karrenfeld. It is, however, certain that the material between the pinnacles represents reef debris that was subsequently phosphatized. This debris, which is apparently similar to the broken coral fragments, sand, and

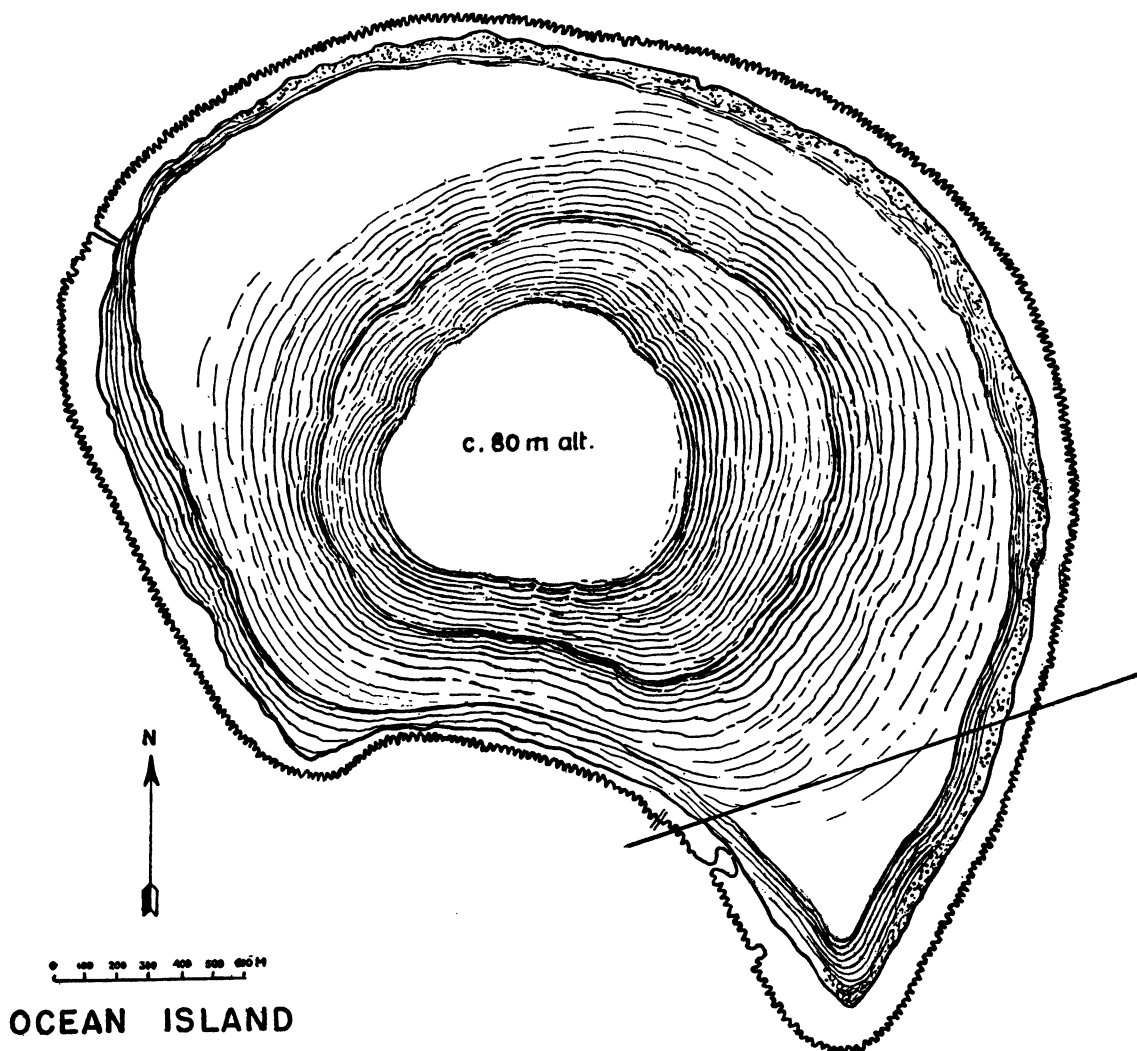


FIG. 57. Map of Ocean Island. After Ellis.

sides, whereas weathering of exposed coral rock now produces pitting, particularly near the coast. He does not seem to have considered the possibility of subaerial dissection under climatic conditions other than those now prevailing (cf. Elschner, 1913; Blackwelder, 1925). The champignon of Aldabra and other islands of the western Indian Ocean

oolitic and pisolitic bodies found in modern reefs, certainly implies a period of submergence after the Karrenfeld was formed. Owen, moreover, states that phosphatized corals have been found *in situ* attached to pinnacles.

Two main kinds of phosphate are distinguished by Power and by Owen. One type is called incoherent by the latter and alluvial

by the former; the other type is termed coherent by Owen and rock by Power. Inasmuch as the term alluvial gives a false impression of origin, Owen's terminology will be used. Incoherent phosphate consists of pebbles, pisolitic and oolitic grains, and finer pulverulent material. When wet the incoherent phosphate generally forms a clay-like mass in which the larger fragments are embedded. In color the incoherent phosphate varies from leather brown in poorer grades to pale buff in higher grades, which in general are the more clay-like. Owen regards the finer material of the incoherent phosphate as partly derived from the residual material of guano and partly from rapid interaction of guano solutions and coral rock. The coarser

liquid. Microscopically the translucent phosphate is entirely isotropic. Owen, following Elschner, who described similar material from Nauru as nauruite, considers that the translucent phosphate was formed by gelation of a residual colloidal solution, after metasomatism had been effected.

Throughout the island the surface is covered with black phosphatic soil, containing about 18% organic matter and combined water, and about 30% P_2O_5 . This passes rapidly but imperceptibly into the true phosphate deposit, which shows little change in composition until the dolomite rock is reached. The maximum content of phosphate is 42.1%, the minimum 36.2% P_2O_5 . The deposit is found generally to be thickest in

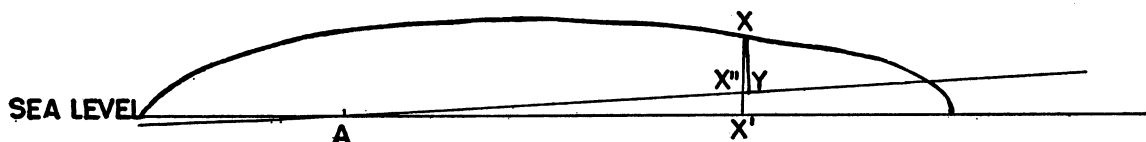


FIG. 58. Section through Ocean Island showing base level. After Owen.

incoherent phosphate was clearly formed by the phosphatization of pisolitic and oolitic grains of calcium carbonate. Such grains, with a markedly concretionary structure, are well known on many reefs. Coherent phosphate is of three kinds. The first kind is described as fragmental and consists of large pieces of phosphatized detrital limestone of types ordinarily found on coral reefs. It is found irregularly embedded in the incoherent phosphate that forms the main deposit. The second type of coherent phosphate consists of phosphatized coral rock *in situ*, namely, the pinnacles of the Karrenfeld on which the other deposits rest and which in places are in part phosphatized, and occasional corals *in situ* attached to such pinnacles. The third variety of coherent phosphate is termed translucent or subvitreous. It is found in finely laminated masses, as a cementing ingredient, as an outside coating on phosphatized coral, and as a lining to cavities within the unphosphatized coral rock. It is said to contain less minor constituents than do the results of metasomatism. Casts of bubbles are often present, indicating that the material has formed as the result of solidification of a

the central part of the island. At any point on the island the variation in composition throughout the section is small, rarely amounting to 0.46% P_2O_5 (1% $Ca_3P_2O_8$). The mean value for the top and bottom at any locality varies in a quite systematic manner, so that if the values are entered on a map a series of isophosphatic contours can be drawn. These contours dip at $0^\circ 17'$ towards the south-southwest, and on the shore of the island in this direction the lowest phosphate is covered by the sea. Owen claims that the change in composition is so regular that the phosphate content as $Ca_3P_2O_8$ at any point X can be determined from the expression

$$80 + 0.04 (\text{elevation of } X \text{ above sea level}) - 0.04 (XA \text{ feet } \tan 0^\circ 17')$$

where XA represents the perpendicular drawn from X to the line made by the intersection of the plane of the 80% $Ca_3P_2O_8$ contour with sea level (fig. 58).

The best analyses of Ocean Island phosphate are by Elschner (I), Owen (II), and by Jacob, Hill, Marshall, and Reynolds (III):

	I	II	III
H ₂ O and ignitable matter	3.62%	2.5 %	1.88%
Na ₂ O	n.d.	n.d.	0.49
K ₂ O	n.d.	n.d.	tr.
CaO	52.95	50.05	54.08
MgO	0.08	0.03	0.00
(Al,Fe) ₂ O ₃	—	0.07	0.20
(Al,Fe)PO ₄	0.81	—	—
P ₂ O ₅	39.05	40.1	40.32
CO ₂	1.93	1.54	1.06
SO ₃	0.07	0.29	0.00
SiO ₂	0.39	1.0	0.40
F	2.05	1.46	2.97
Cl	n.d.	n.d.	0.01

Ellis says that the average phosphate content of shipments from 1921 to 1934 was 40.4% P₂O₅. It is possible that Elschner's, and probable that Owen's, fluorine determinations are too low; the same discrepancy appears when Elschner's Nauru determinations are compared with those of Jacob, Hill, Marshall, and Reynolds. The latter investigators analyzed two other Ocean Island samples for fluoride, the three samples that they used giving:

	MEAN			
P ₂ O ₅	40.32%	40.33%	40.87%	40.51%
F	2.97	2.97	3.29	3.08
F:P ₂ O ₅	0.0737	0.0736	0.0805	0.0761

Elschner comments on the amount of fluorine in Ocean Island phosphate and indicates that the fact that the element is more abundant in such material than in Nauru phosphate was well known in the phosphate trade. He gives 1.3% to 2.3% as normal. Ellis says Ocean Island coherent phosphate specially rich in fluoride can be recognized by its resinous luster, but that the amount of such rock rich in fluorine is insufficient to show up in general commercial analysis of a cargo.

Jacob, Hill, Marshall, and Reynolds found 18.3 milligrams per kilo of iodine in the sample that they used for a complete analysis.

The best estimate of the total amount of phosphate on Ocean Island is probably that of Ellis (1936) who was responsible for the discovery of the deposit and who was long associated with the Pacific Phosphate Company and later was on the Board of Phosphate Commissioners. The figure that he gives, namely, 20,000,000 tons, is kindly con-

firmed by the British Phosphate Commissioners (*in litt.*, March 26, 1946). Stutzer, without quoting his authority, gives 30,000,000 tons, which is certainly excessive.

Power considered that the first step in phosphatization consisted of the filling of cracks in the coral rock with phosphate. The coral was then removed by marine denudation, but the harder phosphate remained and so was concentrated as primary alluvial phosphate; this later was cemented to form secondary rock phosphate. Such a process is very improbable and was rejected by Owen, whose account of the history of the island may be summarized thus:

1. Elevation in at least three stages.
2. Subaerial dissection producing a Karrenfeld, comparable to the modern champignon of Aldabra (p. 298) but more impressive.
3. Submergence, during which corals could attach to the pinnacles of the Karrenfeld, and reef debris could collect between them. This seems to be the most likely time for the occurrence of dolomitization.
4. Emergence apparently occurring quite regularly, as the isophosphatic contours are regular. During the emergence birds colonized the island in enormous numbers. Solutions leached from the guano phosphatized the underlying coral rock and its detrital products. On evaporation such solutions deposited the isotropic, colloidal, translucent phosphate. The existence of the latter strongly suggests a moderate to low rainfall of very markedly seasonal character. The bird colony must have persisted until the present degree of emergence was achieved, but the older central part of the colony would have had a longer existence, so producing a thicker and somewhat more phosphatic deposit.

5. A slight tilting along an east-northeast, west-southwest axis of about 0° 17'.

6. A drop in sea level of about 2 feet indicated without evidence or comment by Owen.

Owen suggests that the magnesium of the dolomite is derived from guano, but this suggestion is probably quantitatively impossible and is inapplicable to the numerous islands of the Pacific consisting of Tertiary dolomitized limestone without phosphatic deposits.

NAURU

LATITUDE $0^{\circ} 25' S.$, LONGITUDE $166^{\circ} 57' E.$

An elliptical island about 6 kilometers long in a northeast-southwest direction and about 4.7 kilometers broad (fig. 59). The maximum elevation above sea level is 65 meters. Nauru has a more complex structure than Ocean Island, but until the island is reinvestigated

by a competent geologist interested in all phases of its history many important aspects of that history will remain obscure. The only significant sources of information about the island are the contributions of Power (1905) and of Elschner (1913). An article by the ethnologist Hambruck (1914) evidently leans heavily on information supplied by Elschner. A short paper by Bohne (1926) summarizes

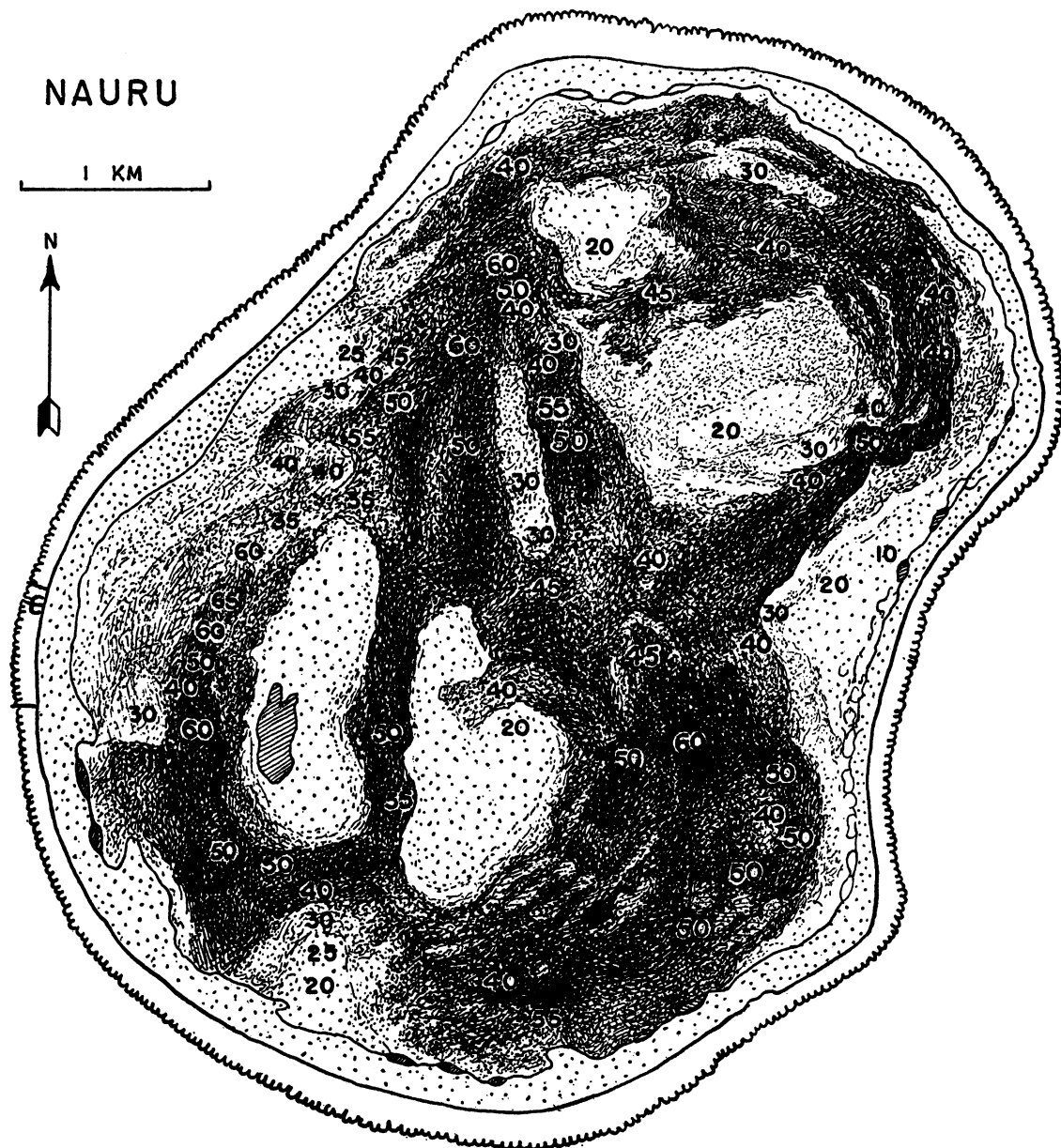


FIG. 59. Map of Nauru.

the previous work, adding a number of details, very few of which, however, bear on any of the important unelucidated problems presented by the island. Other contributions contain nothing of interest not recorded by Power and by Elschner. A good bibliography is given in Ellis' book on Ocean Island and Nauru; this book, however, is entirely unreliable in its more theoretical scientific discussions. The following account is based almost exclusively on the descriptions of Power and Elschner. Power's belief that the concentration of the primary phosphatic material was due to marine erosion of the coral rock which he supposes enclosed it is, however, no more acceptable for the Nauru deposit than for that of Ocean Island.

Nauru is surrounded by a fringing reef, which is steep or, according to Elschner's diagram, even concave on the seaward edge, and which reaches a maximum width of 300 meters along the northern shore of the island. The upper part of the tidal reef is covered with coral sand and debris. Within this littoral is a flat coastal plain regarded by Power as a covered continuation of the reef platform, and bearing coconut palms. Coral debris is, according to Bohne, piled up to form a series of low ramparts along the shore. The inner margin of the littoral plain is marked with depressions and brackish ponds, supposed by Bohne to be the remains of the lagoon of a barrier reef. Elschner says that on the west side, where the coastal plain is widest, the whole is of recent origin but that on the eastern side only the outer reef wall is recent. On the eastern shore there are dolomitized pinnacles within the tidal reef zone, indicating submergence of part of the island on this side.

The interior mass rises rather suddenly from within the coastal plain. In many places, notably along the east side of the island, the slope is marked by numerous dolomite pinnacles. The whole upland is dissected to form a Karrenfeld, but this is apparent in most places only after the removal of the phosphate capping. The highest point lies in from the western part of the island and overlooks a deep depression, completely surrounded by high ground and containing a shallow lake, 1.6 meters (5 feet) deep with a mud bottom about 60 cm. (2 feet) thick (Power). Bohne

says that the depth is not more than 1 meter at times of heavy rain. The water in the lake was roughly analyzed by Power and found to contain material in the following proportions:

		APPARENT CORRE- SPONDENCE IN GRAMS PER LITER
Cl	24.8137	1.363
SO ₃	2.0472	0.1127
P ₂ O ₅	0.5731	0.0315
Siliceous matter	0.8680	0.0477
(Al,Fe) ₂ O ₃	0.2100	0.0115
CaO	6.2667	0.344
MgO	1.2463	0.684
Na ₂ O, K ₂ O	43.000 (?)	2.136 (?)

The units are not given, but the phosphate is said to correspond to 3.645 grains of Ca(H₂PO₄)₂ per gallon, i.e., 0.0315 grams of P₂O₅ per liter. The figures given above in the second column are computed on the basis of this proportionality, but no great reliance can be placed on the results. The air-dried mud of the lagoon had the following composition:

H ₂ O at 100°C.	11.19%
Organic and combined H ₂ O	47.31
(Al,Fe) ₂ O ₃	0.70
Ca ₃ P ₂ O ₈	33.86
CaSO ₄	3.46
CaCO ₃	1.92
CaO (probably organic)	0.79
MgO, alkalis	0.56
SiO ₂	0.21

Since the water shows a delayed tidal rise and fall there must be an underground connection with the sea, or at least a transfer of pressure through the coral rock. Power notes that the phosphate rock holds water better than the coral and that depressions lined with phosphate can be recognized by having larger trees (tamano) than other parts of the island. The lake is considered by the principal investigators of the island to represent the lagoon of an atoll, though A. Agassiz (1903) considered that it was formed by chemical denudation. The basin is crossed by old reef banks, in places apparently broken as if by tectonic action. The rim at the top is crowned with dolomite and phosphatic rocks, dissected into fantastic forms 10 or more meters high. The dolomite, weathering grayish black, angular, and rough, is, according to

Bohne, easily distinguished from the smoother, rounder, light yellowish phosphate. Power noted that lichens grew better on the latter than the former, while Bohne remarks that the phosphate rock has a fair flora of lichens, mosses, and algae. The northeastern part of the island contains three irregular basins, the lowest points of which lie at about 20 meters above sea level and are dry. The ridges between the depressions are regarded by all authors as barrier reefs formed in association with the original atoll. Elschner states that

whole of the island appears to be more or less dolomitized. Elschner gives analyses, mainly from relatively superficial exposures. The analyses, omitting one described as infiltration in aragonite, from the modern reef, indicate from 29.91% to 44.31% MgCO_3 . Pure dolomite contains 45.65% MgCO_3 and 54.65% CaCO_3 . The Nauru dolomites usually contain a little more CaCO_3 than this, though calcium is not given in all Elschner's analyses. There is 0.27% to 0.46% $(\text{Al,Fe})_2\text{O}_3$ in the consolidated dolomite and rather more in

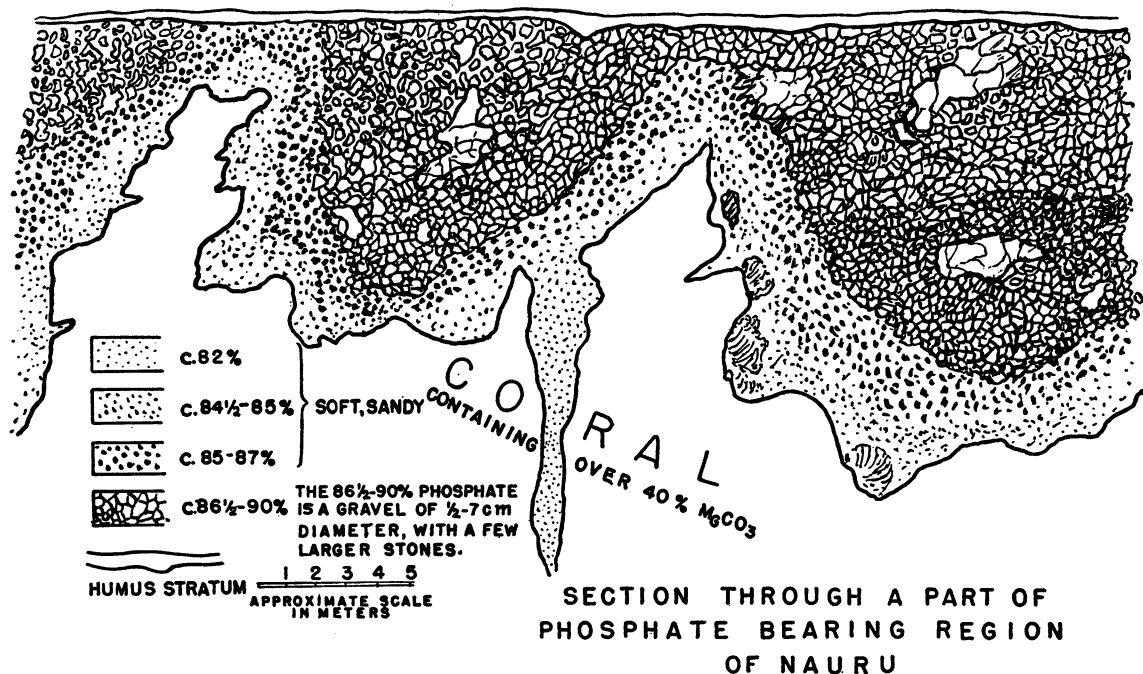


FIG. 60. Section through part of phosphate field on Nauru. After Elschner.

pinnacles within the old basins are often marked with water-cut lines, which may be displaced from the horizontal.

Power notes planes in pinnacles behind "Rashes station" to be inclined and comments on stalactites in caves that are not vertical. Elschner's remarks confirm such tilting, while Bohne says that in the southwestern part of the island pinnacles and stalactites are inclined 20° to the northeast. This inclination is so great that it is curious that neither of the earlier authors noticed it except in the most casual manner.

Apart from phosphate rock and material derived from the modern reef, almost the

consolidated dolomite mud from the east side of the reef. Bohne states that in no case is the molecular ratio $\text{MgCO}_3:\text{CaCO}_3$ quite equal to unity and that pure calcium carbonate coral cores may be found in dolomite in the caves.

The phosphate of Nauru forms a cap over the entire dissected upland, filling up the depressions in the Karrenfeld and forming a relatively even surface on which there is a thin layer of black phosphatic soil (fig. 60). Only when the phosphate is removed by quarrying is the extraordinarily dissected nature of the interior apparent.

According to Elschner the cavities of the

Karrenfeld typically are filled with a soft sandy phosphate containing about 37.50% P_2O_5 at the bottom. This layer, which may be a meter or two thick, passes into a somewhat richer sandy phosphate containing 39% to 40% P_2O_5 . The main filling of the larger, wider cavities is, however, formed of detrital fragments mostly 0.5 to 7.0 cm. across containing 39% to 41% P_2O_5 . Embedded in this material are occasional large phosphatic blocks. At least in many places the boundary between phosphate and dolomitized coral is quite sharp. As on Ocean Island cracks and depressions may be filled with agate-like or translucent phosphate, termed nauruite. Ellis claims that the general appearance of Ocean and Nauru rock is somewhat different, the specimens from the former locality being much more diverse than from the latter.

According to Bohne there are a few localities in which phosphate lies between dolomite in a pinnacle or, lying over dolomite, is covered with younger reef formations. These localities led him to believe that there were two periods of phosphatization separated by a submergence. The existence of such occurrences is also indicated by Elschner in a footnote (1913, p. 42), but the context suggests that he considered the phosphate below unphosphatized rock to have been deposited in cracks and channels and to be younger rather than older than the overburden. Power describes phosphate forming tubular stumps on the reef, apparently owing to phosphatic material filling a channel or blow hole. Ellis (1936) records that in 1929 a well was drilled on a flat coastal belt; the following stratigraphy was noted:

Coral sand	12 feet
Coral conglomerate	5 feet 6 inches
Semi-loose, flaky coral with white coral slime, and loose coral gravel with few pieces of coarse alluvial phosphate	3 feet
Alluvial phosphate	6 or ?10 feet

Evidence of a pinnacle in the well wall was obtained. The phosphatic material lay at least 3 meters (9 feet) below the level of the reef exposed at low tide. Phosphatization therefore evidently occurred when the island was more elevated than it is today, and when a part of the Karrenfeld now largely destroyed spread out over the area at present

occupied by fringing reef.

The best analyses of Nauru phosphate follow. The first two are from Elschner, I being of unspecified nature, II being from 22 feet in a working, under high-grade phosphate. As indicated above many samples show slightly higher phosphate content, but no others of Elschner's 14 analyses have fluorine determinations. The third analysis (III) is from Jacob, Hill, Marshall, and Reynolds (1933).

	I	II	III
H ₂ O	1.70%	3.40%	2.78%
Ignitable matter	3.30		
Na ₂ O	n.d.	n.d.	0.45
K ₂ O	n.d.	n.d.	tr.
CaO	52.47	52.06	54.42
MgO	0.21	0.27	0.00
Al ₂ O ₃	0.53	0.13	0.30
Fe ₂ O ₃		0.24	
P ₂ O ₅	38.72	39.35	38.92
CO ₂	1.88	2.12	2.04
SO ₃	0.22	n.d.	0.00
SiO ₂	n.d.	n.d.	0.20
F	1.60	1.80	2.62
Cl	n.d.	n.d.	0.01

Ellis (1936) says that the mean content of phosphate in shipments quarried between 1921 and 1934 was 39.1% P_2O_5 . Owen, following earlier authors, without direct evidence, considered the excess of CaO was combined with organic matter and criticizes Elschner's chemical interpretation of the material as $(Ca_3P_2O_8) \cdot x(Ca[F_2O, (OH)_2])$. There can, however, be little or no doubt that the Nauru material at its purest represents a more or less isotropic or cryptocrystalline apatite-like mineral. Rogers (1922) considered nauruite to be the purest collophane known to him. A modern mineralogical interpretation would place the mineral as francolite or hydroxyl-fluor-carbonate apatite, essentially as Elschner believed.

In addition to their complete analysis, Jacob, Hill, Marshall, and Reynolds give two other phosphate and fluorine analyses, the three samples they used giving:

	MEAN			
P ₂ O ₅	38.92%	39.06%	39.21%	39.06
F	2.62	2.48	2.10	2.40
F:P ₂ O ₅	0.0673	0.0635	0.0536	0.0614

They also found 16.5 milligrams per kilo of iodine in the sample containing 38.92%

P_2O_5 . This result is concordant with two earlier determinations by Wilke-Dorfurt, Beck, and Pleff (1928) who found 16.7 milligrams per kilo and 19.05 milligrams per kilo in two samples of Nauru phosphate.

Elschner (1913) indicates that the island was originally considered to bear 42,000,000 tons of phosphate, but that this estimate was much too low. Ellis (1936), doubtless reflecting official opinion, believed 90,000,000 tons to be a conservative estimate. The British Phosphate Commissioners (*in litt.*) kindly indicate that the reserve was originally approximately 87,500,000 tons, a figure accepted in subsequent discussions. These estimates are lower than the one implied by Elschner who regarded the mean depth to be 5 to 6 meters over an area of 18 km².

Agassiz considered Nauru to be composed of limestones comparable to those of Eva, Vavau, and other islands of the Tonga group. Elschner believed that the phosphate and dolomite of Nauru were of Tertiary age. He indicates that a rich collection of fossil corals and other paleontological material, apparently collected by him, was deposited in the University Museum at Giessen. He states that while the same organisms occur in the southwest and northeastern parts of the island different species are dominant, the northeast part probably having much algal material. Bohne says that the fossil corals of the island are mainly Tertiary but gives no determinations. He claims, as did Elschner, that different forms dominate in the different parts of the island. He supposes that this implies that the dolomitized coral rock of the northeast and southwest parts of the island are derived from reefs flourishing at different times. Essentially following Elschner he considers that the older atoll around the lake

was elevated and dissected and at that time a preëxisting gentle slope on the northeast side became suitable for coral growth, the reefs so formed enclosing three lagoons. Subsidence later occurred, and then emergence, followed by dissection of the whole island. Alternatively he supposes that the second emergence took place quickly on the southwest and slowly with reef growth on the northeast. No faults are described, but the tilting of the southwest part of the island must imply faulting along a northwest-southeast axis. Though the fault is obscured, Bohne thinks it is represented by a trough which runs about north by west and south by east through the center of the island, separating the Buada depression and the less deep depression on its east from the two northeastern depressions. Bohne's chronology implies two periods of emergence, with dissection and phosphatization following each emergence. Actually the evidence for this is meager. So far as phosphatization is concerned it is merely that in a few places phosphate underlies dolomite, which means little in a highly fissured mass of material. There seems to be no evidence that two periods of dissection occurred except for the fact that cavities existed in which the products of the supposed first phosphatization could collect. So far as can be ascertained from the available information, the history of Nauru has been essentially like that of Ocean Island save that the first emergence proceeded without interruption. There has evidently been some submergence subsequent to phosphatization. Whatever tilting and faulting have occurred took place after the formation of the Karrenfeld, presumably at the time of the second elevation of the island.

RAISED PHOSPHATIZED ATOLLS AND OTHER ISLANDS IN THE WESTERN PACIFIC¹

Phosphatic deposits are known on a large number of islands in the western part of the Pacific north of New Guinea and for the most part north of the Equator (fig. 61). Most of these islands lie in very wet regions, where the precipitation is in excess of 2000 mm. and may reach 4000 mm. per annum.

Evidence of contemporary phosphatiza-

tion is very slight, and it seems certain that most of the phosphatization now observed took place at some time in the past. It is, however, almost equally certain that the deposits on some islands are older than on others.

¹ Since the above was written, an important paper (Nugent, 1948) has appeared on the phosphatized is-

The islands are conveniently presented in three groups:

1. Phosphatized islands of the Purdy and Ninigo groups, Admiralty Islands, and in the Schouten Islands.

2. Phosphatized islands in the Marshall, Caroline, Palau, and Mariana groups, with outlying islands.

3. Phosphatized islands in the Borodino and Riu Kiu groups and other localities south of Japan.

PHOSPHATIC DEPOSITS ON ISLANDS OF THE PURDY AND NINIGO GROUPS, ADMIRALTY ISLANDS, AND ON THE SCHOUTEN ISLANDS

Three groups of phosphatic islands lying north of New Guinea and just south of the Equator may be conveniently considered together. The phosphatization on these islands is certainly ancient and quite possibly occurred at different times on the different islands.

The region in general is one of very high rainfall. No records referring to the phosphatized islands themselves are available, but neighboring stations, indicated, for example, in Schott (1935), may suggest a mean annual precipitation of between 2000 and 3000 mm. The "Atlas of climatic charts of the oceans" (McDonald, 1938) indicates steady rain for 5% of the observations at Greenwich Mean noon throughout the year, and around the Admiralty Islands for 10% of such observations between March and August.

THE PURDY ISLANDS

A group of five very slightly elevated atolls, known as:

North Bat Island, latitude 2° 50' S., longitude 146° 14' E.

South Bat Island, latitude 2° 50' S., longitude 146° 14' E.

lands in the western part of the Pacific Ocean. Most of Nugent's discussion is directed towards the problems presented by the islands themselves rather than those specifically raised by the phosphate deposits. He concludes that the phosphatization of all of them is of pre-Wisconsin age, and even extends this conclusion to the Line Islands and other members of the central Polynesian Sporades, including Vostok. This conclusion is of course not acceptable. Nugent gives indications of a phosphate deposit on Minami Daito Jima, which otherwise does not figure in the literature of phosphatic islands.

Mole Island, latitude 2° 51' S., longitude 146° 26' E.

Mouse Island, latitude 2° 52' S., longitude 146° 23' E.

Rat Island, latitude 2° 57' S., longitude 146° 20' E.

Phosphate was worked in 1890 when 1000 tons were exported to Germany (Seidel, 1891) and again for a short time about 1910. The best account is given by R. C. Hutchinson (1941). The islands are all surrounded by fringing reefs, those of the two Bat Islands being apparently continuous. The islands themselves are sandy, with a well-defined rim about 2 meters high and a central depression corresponding to the lagoon, the lowest point of which is elevated about 60 cm. above high tide mark. The islands are said to be covered with coconuts, ferns, and vines, and on some there are various other shrubs and trees. The central depressions are said to be swampy in wet weather.

The phosphate deposits (fig. 62) on Mole and Mouse Islands occupy the central part of the former lagoon and are covered with a few inches of sandy soil. The phosphatic material is described as light in weight, of specific gravity 1.6-1.8, very porous and of a light or medium brown color. It occurs as lumps weighing 1 to 4 kilograms and is very heterogeneous, small white particles of shell and coral being included within the brown phosphatized masses. On the two Bat Islands the deposit is eccentrically situated so that on the north side of North Bat and the southwest side of South Bat it is exposed on the shore of the island. Hutchinson supposes that the sandy parts of the two islands have moved towards each other in recent times, leaving the phosphate deposits to mark the old central parts of the lagoons. It is also possible that there has been slight local tilting on either side of an axis running between the islands. Rat Island, which is the smallest of the five islands, is not specifically stated to have a deposit.

Hutchinson gives the following analyses:

	MOLE	MOUSE	NORTH BAT	SOUTH BAT
H ₂ O	8.9%	5.7%	5.9%	7.2%
Ignition loss	24.6	32.9	26.4	26.6
CaO	52.2	53.2	49.7	50.5
P ₂ O ₅	11.7	11.2	10.4	10.0
Insol.	0.15	0.27	0.14	0.21

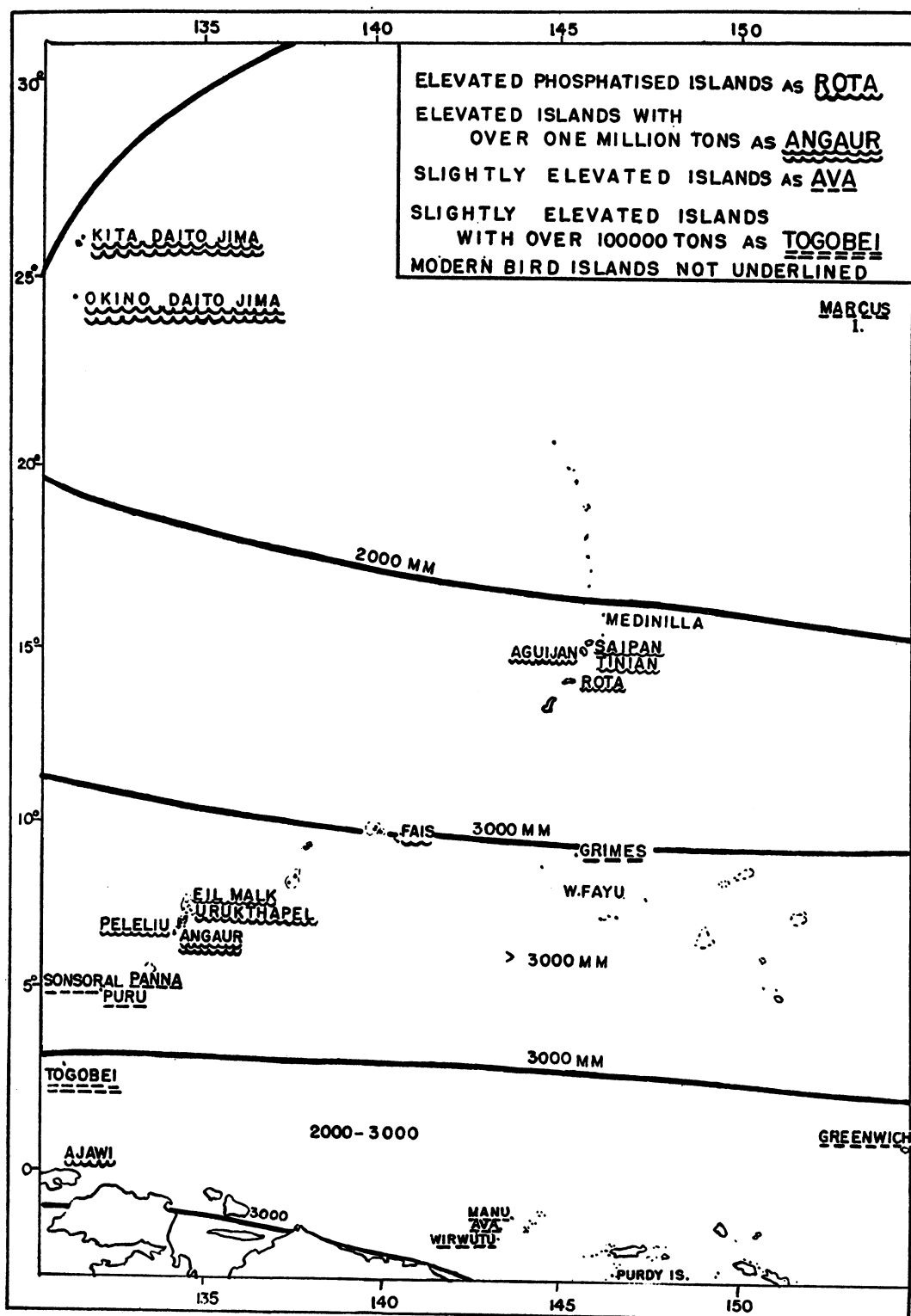


FIG. 61. Map of the western Pacific.

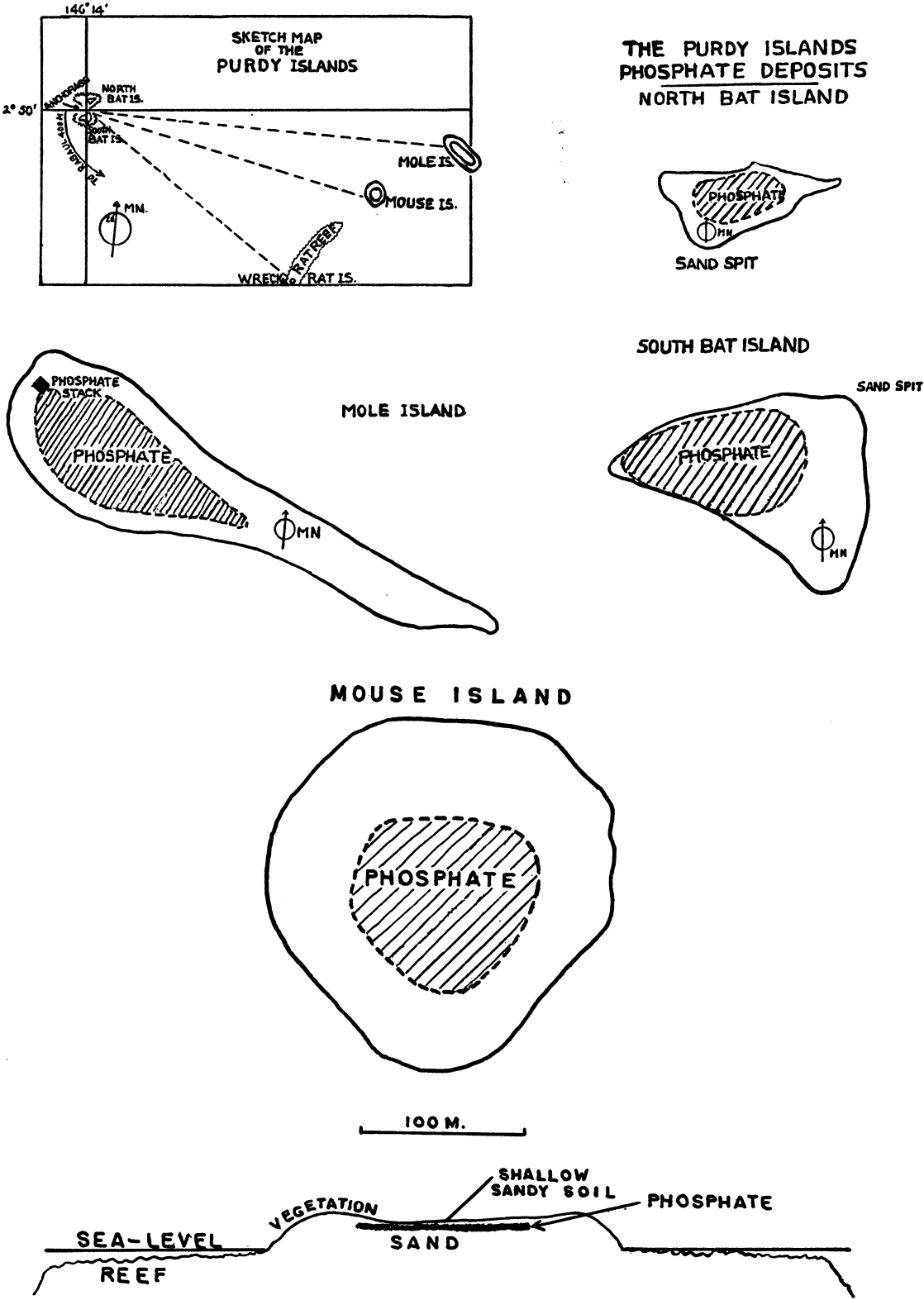


FIG. 62. Map of the Purdy Islands, with a section through Mouse Island. After Hutchinson.

Much of the ignition loss, though treated as organic matter in the text, must be CO_2 . It is obvious that only about one-quarter of the material can be calcium phosphate. The total mass of phosphate was estimated on the assumption that the mean thickness of the bed was 3 inches (7.6 cm.), though the mean value actually obtained from 32 borings in different islands was 5 inches (13.7 cm.) and the maximum thickness was 3 feet.

The values obtained are given below and can be used to determine the total amount of P_2O_5 on the islands:

	TONS	TONS P_2O_5
Mole	10,200	1,190
Mouse	5,000	560
North Bat	2,400	250
South Bat	9,400	940

ELIZABETH OR ALIM ISLAND

LATITUDE $2^\circ 51' \text{ S.}$, LONGITUDE $147^\circ 07' \text{ E.}$

Said by the "Pacific islands pilot" (United States Hydrographic Office, 1920a) to be a large, flat, platform-shaped island. Meise, on the authority of Nevermann (*in litt.*) lists the island as bearing phosphate or guano. R.C. Hutchinson, however, enters Alim as one in a table of islands examined, mainly in 1909 by Friederici, without workable phosphate's being discovered. The island is said to be composed of coral lime, and no indication of any phosphate is entered in the table. This negative evidence is probably significant in that Hutchinson gives in this list traces of P_2O_5 for a locality called Dylup Plantation and 0.21% P_2O_5 for limestone from the Talele Islands off New Britain. Alim must be regarded as a very doubtful phosphatic island.

THE NINIGO (L'ECHEQUIER) ISLANDS

A group of 53 small islands, with three more isolated islands to the south. These three isolated islands bear phosphate:

Manu or Allison Island, latitude $1^\circ 17' \text{ S.}$, longitude $143^\circ 41' \text{ E.}$

Aua or Durour Island, latitude $1^\circ 27' \text{ S.}$, longitude $143^\circ 06' \text{ E.}$

Wuvulu or Maty Island, latitude $1^\circ 43' \text{ S.}$, longitude $143^\circ 22' \text{ E.}$

The deposits on these islands were examined in 1929 by K. M. Fennel, whose results are

discussed by R. C. Hutchinson (1941). Manu Island is said to be a small island rising 4 feet only above sea level, though the "Pacific islands pilot" (vol. 1) gives a maximum elevation of 60 feet. The phosphate deposit is small. Aua is an elongate island nearly 5 kilometers long, surrounded by a reef. The phosphate deposit lies about 400 meters inland on the southeastern part of the island, forming a strip about 900 meters long, 27.5 to 137 meters wide, and 1.8 to 2.4 meters deep. The total reserve was estimated as not more than 80,000 tons. It is said to consist almost entirely of rock phosphate, with little alluvial material. The phosphate is mixed with broken coral rock, sand and mud, and covered with ferns and creepers. Where rock phosphate is exposed it is overgrown with moss. Wuvulu is a still larger island, with phosphate scattered over an area of about 4000 square meters in the southwestern part of the island. The material is almost all rock phosphate, but the dense jungle makes estimate of its quantity difficult. The general appearance of the rock from these three islands is said to be like that from the Purdy Islands. Unfortunately no analyses have been published.

AJAWI OR MIOS KAIRU

LATITUDE $00^\circ 16\frac{1}{2}' \text{ S.}$, LONGITUDE $135^\circ 05' \text{ E.}$

A small island at the northwest end of the Schouten group. According to Wichmann (1915) the greater part of the island is low, but the eastern section has fantastically shaped rock pinnacles up to 16 meters high. The low part, about 3 meters above sea level, consists of coral rock and sand with a coarse white porous limestone containing specimens of subrecent *Rotalia*. This part of the island is covered with *Pandanus*.

In the eastern part of Ajawi there is a compact limestone containing *Globigerina* and probably of at least early Miocene age. The fantastic rocks observable from the sea on this side of the island proved to be phosphorite not unlike that of Nauru. The material is in general light yellowish and amorphous; dark spots of organic matter occur in the phosphate mass, and cavities may be lined with banded, agate-like phosphate. Wichmann gives no data on the relationship

of the phosphatic rock to the Tertiary limestone, nor any details permitting conclusions about the time relations of phosphatization and dissection on the island. The following analysis is given:

H ₂ O at 110°C.	1.48%
H ₂ O at 110°-125°C.	3.86
CaO	37.38
MgO	2.17
Fe ₂ O ₃	2.83
P ₂ O ₅	31.53
CO ₂	7.31
Insol.	0.19
	86.75

The material unaccounted for is said to be largely organic. Fluorine and a trace of chlorine were also shown to be present. The specific gravity is 2.78 and the hardness 6. It is evident that the Ajawi rock is a much more consolidated material than that from the Purdy Islands. It differs from the rock phosphates of the elevated islands in the central Pacific in its apparently high organic content.

PHOSPHATIZED ISLANDS IN THE MARSHALL,
CAROLINE, PALAU, AND MARIANA GROUPS,
WITH OUTLYING ISLANDS

The islands to be considered are largely limestone covered but may have exposures of

volcanic rocks forming their cores. Tayama (1939) considers that the limestones and the terraces representing the depositional surfaces of the reef forming these limestones constitute the stratigraphic sequence here given in table 17.

The evidence for the scheme in table 17 is lithological and paleontological, as the terrace levels vary from group to group, showing vertical movements of the islands.

Nearly all the islands to be considered in this section have very high mean annual rainfalls. In the region of the equatorial rain belt, about latitude 5° N., the annual precipitation is evidently usually above 3000 mm. per annum, reaching just over 4000 mm. per annum in the southern Palau Islands and at Ponape. The Marianas are somewhat drier, receiving in general about 2000 mm. per annum. Such rainfalls are also probably characteristic of the islands south of Japan. Marcus Island alone of the localities to be discussed probably has a mean annual rainfall not exceeding 1500 mm. per annum. There appear to be some bird islands in this region. Hambruck (1914) mentions West Faiu, Gaspar Rico, and Magur as having incredible numbers of birds, and the "Pacific islands pilot" indicates that Lutke or Fagan Pissila is visited by the Caroline Islanders for sea birds. Apart from Gaspar Rico, which is,

TABLE 17

HOLOCENE	Raised limestone and other deposits	
	Raised beach and younger raised reef	Post-Peleliu terrace
Unconformity		
	Older raised reef	Peleliu terrace
PLEISTOCENE—Unconformity		
	Terrace deposits	
Unconformity		
PLIO-PLEISTOCENE	Mariana-Palau limestone	Mariana terraces at three levels
	<i>Halimeda</i> formation	Pre-Mariana terrace 3
Unconformity		
MIOCENE	<i>Nephrolepidina</i> formation	Pre-Mariana terraces 1 and 2
Unconformity		
	<i>Eulepidina</i> formation	
OLIGOCENE—Unconformity		
	<i>Densinyama</i> formation	
Unconformity		
EOCENE	<i>Camerina</i> formation	
Unconformity		
PRE-TERTIARY		

however, not mentioned in Aso's (1940) work on the phosphate islands formerly under Japanese control, these islands are not regarded as having deposits.

BIKAR ATOLL

LATITUDE 12° 15' N., LONGITUDE 170° 07' E.

Bears three islands, Bikar, Arumenii, and Jaboerukku. The islands are richly vegetated, but without permanent inhabitants. The "Pacific islands pilot" mentions a corrugated iron hut used by Japanese bird catchers on the second island from the north; this presumably implies a bird colony, but there is clear evidence that the phosphatization is not due to a contemporary avian population. Small phosphate deposits are found on all three islands (Aso, 1940). On Bikar Island the deposit has an area of 62,100 m² and varies in depth from about 9 cm. to about 30 cm., the mean thickness being about 19.8 cm. The deposit occurs in a thickly wooded part of the island and is covered, except in one small area, by a layer of coral pebbles. The thickness of this layer may be 76 cm. in places. Part of the phosphate is stained by dark extractive material from decaying vegetation. The overburden of coral pebbles has presumably been washed or blown over the phosphate prior to the establishment of a dense vegetation cover.

The deposits on the other two islands are inadequately described. There appear to be about 900 tons of black earthy phosphate on Arumenii; no details of the Jaboerukku deposit are available, beyond those of the analysis:

	P ₂ O ₅	CaO	(Al,Fe) ₂ O ₃
Bikar nodular	25.54%	47.72%	0.18%
Bikar nodular	5.88	49.05	0.19
Arumenii, black earthy ^a	14.65	25.74	negligible
Jaboerukku nodular	23.38	49.96	0.37

^a This analysis is also given, no doubt in error, as referring to earthy phosphate from Jaboerukku.

POKAAKKU, TAOGNI, OR GASPAR RICO ATOLL

LATITUDE 14° 38' N., LONGITUDE 168° 59' E.

The most northern of the Marshall Islands, a little known atoll bearing low islets thinly covered with bushes and *Casuarina*. It was

evidently the site of a bird colony as the "Pacific islands pilot" (United States Hydrographic Office, 1928) indicates that it was raided by Japanese plume hunters. Liesegang (1940) states that a commercially inconsequential deposit containing 1.8% to 5.5% P₂O₅ has been found on the atoll. Aso does not mention the island.

EBON

LATITUDE 4° 37' N., LONGITUDE 168° 45' E.

On the southern edge of the Marshall group, a rather large and apparently unelevated atoll bearing 21 well-wooded and fertile islands. The main island of Ebon is said by Aso (1940) to have an area of about 3 square kilometers; in the center of the island an area of about 264,000 m² bears phosphate. In places the upper layers of phosphate are covered with brown clay; in other places nodular phosphate appears at the surface. In the lower part of the deposit high-grade rock phosphate, often ash white or yellow brown in color, occupies basin-like depressions in the underlying limestone. The material is said to be friable and to have a high water content. The following analyses made in Japan were supplied by Dr. John Rodgers:

	H ₂ O	P ₂ O ₅	(Al,Fe) ₂ O ₃
Imported 1940	27.34%	23.82%	0.05%
1943	31.03	18.19	0.12

Aso gives the following determinations indicating a more phosphatic material:

	P ₂ O ₅	(Al,Fe) ₂ O ₃
Sandy phosphate (mean)	33.22%	0.35%
Nodule (red brown)	37.11	0.24
Nodule (dark)	38.50	0.22

About 70% of the P₂O₅ is soluble in ammonium citrate. An unconfirmed estimate of a total reserve of 60,000 tons was given by Aso. Statistics of the Japanese Ministry of Agriculture and Forestry, available to Rodgers, indicate that 31,000 tons were exported in 1940-1942. Rodgers considers that the present reserve is small.

NGATIK

LATITUDE 5° 00' N., LONGITUDE 157° 17' E.

An atoll bearing nine islets, lying southwest of Ponape. The land surface is said to be fertile and well wooded. Aso (1940) states

that 100,000 tons of good quality phosphate, like that of Ebon, exist on the islets of the atoll. No further details or analyses are available. It is not unlikely that the statement made by Noyes (1944) that the Japanese discovered phosphate on Ponape really refers to this atoll.

GREENWICH, KAPIAGANARANGI,
OR KAPENMAILANG ATOLL

LATITUDE $1^{\circ} 04' N.$, LONGITUDE $154^{\circ} 45' E.$

Bears 28 small islands covered with coconut trees. According to Aso (1940) 14 of the islands have deposits of phosphate. The material is said to be brown, porous, and light, comparable to the better-known phosphate from Togobei. It contains 20% to 37% P_2O_5 and less than 0.8% $(Al,Fe)_2O_3$. The thickness of the deposit varies from about 30 cm. to about 90 cm., and it is said to cover 99,100 m², one islet alone having 33,000 m². The total reserve is given by Aso as 100,000 tons, but not all is worth exploiting.

UDOT ISLAND

LATITUDE $7^{\circ} 20' N.$, LONGITUDE $151^{\circ} 35' E.$

A basalt island in the Truk Archipelago. Aso says that the island bears phosphate but that the deposit is of practically no commercial importance. No details are available.

GAFERUT OR GRIMES ISLAND

LATITUDE $9^{\circ} 14' N.$, LONGITUDE $145^{\circ} 28' E.$

Described in the "Pacific islands pilot" as a moderately high, well-wooded island; it is about 8 kilometers in circumference. Aso says that many sea birds live on the island, but, as it evidently has a fairly rich vegetation cover, it is doubtful if the phosphatization is due to a modern bird colony. The phosphate is described by Aso as greatly resembling the better-known material from Togobei. It contains 10% to 25% P_2O_5 , the mean content being about 15%, and from 0.5% to 1.5% N. The deposit was apparently discovered by the same expedition, sent out by a group of German capitalists in 1903, that discovered the Angaur phosphate. They estimated 18,000 tons to exist on Grimes, but Aso indicates that actually only 5000 to 10,000 tons were present. Statistics of the Japanese Ministry of Agriculture and Forestry, avail-

able to Rodgers, indicate that 747 tons were removed in 1938.

FAIS, FEYS, OR TROMMELIN ISLAND

LATITUDE $9^{\circ} 46' N.$, LONGITUDE $140^{\circ} 31\frac{1}{2}' E.$

In the western Carolines, apparently a typical elevated coral island. It has an area of about 2.5 km² and a maximum elevation of 23 meters. The island has a long axis of 2.4 kilometers set northeast-southwest. On the northwest and southeast sides there is a well-developed but narrow fringing reef. Tayama (1939) recognizes a lower Mariana terrace at 23 meters, Peleliu stage terraces at 20, 15, and 10 meters, and post-Peleliu terraces at 5 and 1 to 2 meters. The center of the island forms a plateau about 20 meters above sea level. The central plateau rises to the highest point on the southwest where there is a well-developed sea cliff. A profile given by Hobbs (1945) indicates the cliff to be about 7.7 meters high; in other parts of the coast there is a low beach. In conformity with its wet, tropical climate the island exports copra and mushrooms as well as phosphate. Aso says that the phosphate field was originally covered with coconuts.

The phosphate deposits are briefly described by Elschner and by Stutzer and have recently been examined by Rodgers (1948). The coral rock of the plateau has weathered into an intricate complex of pinnacles, the crevices between which are filled with the clayey phosphate. Excavated pinnacles, according to Rodgers, stand on an average 1 meter or more (3-4 feet) apart and are 30 to 60 cm. (1-2 feet) in diameter. The crevices are usually 2 meters (at least 6 feet) deep, but many may be found to be deeper. According to the two earlier accounts the mean thickness of the phosphate was 50 cm. The total quantity of phosphate was put by Elschner as 300,000 to 600,000 tons; Stutzer gives the lower figure. Aso, however, says that a German investigator named Herschdonner originally considered 700,000 tons to be present and that this figure was approximately correct. The Japanese statistics, available to Rodgers, indicate that 283,043 tons were exported between 1938 and 1944. Aso says that the material looks like a grayish yellow loam, and normally is equivalent to 80% $Ca_3P_2O_8$, and so is somewhat poorer than that of

Angaur. Rodgers says some phosphate forms a hard incrustation on the rough surface of the coral rock, but that the commercial material between the pinnacles consists partly of hard gray and pink grains the size of bird shot and partly of softer material. An imperfect analysis, relating to commercial material, probably dried at 100° C., is given by Elschner (I). Two others, obtained by Rodgers in Japan, relate to dried (II) and to undried (III) material obtained in 1940:

	I	II	III
H ₂ O	2.08%	3.75%	35.30%
Organic	0.22	—	—
N	0.18	—	—
CaO	49.88	—	—
(Al,Fe) ₂ O ₃	1.62	2.17	1.53
P ₂ O ₅	37.03	35.30	30.08

Aso indicates that earthy phosphate, a soft nodular type, and a pebbly type are present. He states that nodules contain from 36.57% to 37.91% P₂O₅ and 1.97% to 2.20% (Al, Fe)₂O₃. He also notices that a water content of from 15% to 20% is usual in the material as collected.

ANGAUR

LATITUDE 6° 54' N., LONGITUDE 134° 09' E.

The most southern of the Palau Islands, an elevated coral island about 4 kilometers long and having an area of 8 km². The maximum elevation is apparently about 50 meters. The island is roughly triangular, with its southwestern face concave and a much wider fringing reef on the southern coasts than on the northern. Tayama (1939) recognizes a lower Mariana terrace at 50 meters, Peleliu stage terraces at 20 and 10 meters, and a post-Peleliu terrace at 2 to 3 meters. The island is said in the "Pacific islands pilot" (United States Hydrographic Office, 1920a) to be well wooded. The phosphate deposits have been described by Elschner (1913) who, however, was evidently not personally familiar with them, by Stutzer (1932), who largely follows Elschner's account but probably also examined material brought from the island, and by Aso (1940) who had visited the island but who adds little to earlier accounts. Rodgers has also supplied valuable observations. In the higher northwest part of the island, which bears the phosphate, the limestone is weath-

ered to form a Karrenfeld. Elschner suspected dolomitization of the coral had occurred but could give no direct evidence of this. The phosphate covers only a relatively small part of the surface of the island, the total area being but 1 km², distributed in a very irregular manner. The mean thickness within the phosphate field is given by Elschner as 2 meters. The greatest depth of the deposit is over 10 meters, and the bottom may be about 3 meters below sea level. The total quantity present, regarded as 80% Ca₃P₂O₈, is given by Stutzer as 3,000,000 tons, but Aso considers that 2,500,000 tons is a truer estimate of the original reserve. About 1,000,000 tons remained in 1937 and, according to Rodgers, about 400,000 tons in 1946.

Angaur phosphate consists of an earthy phosphate, white or pale gray in color, not distinguishable from clay before analysis, except locally where it shows a pisolitic structure, and a white or brown sandy oolitic phosphate, consisting of discrete grains varying in size from a pin head to a peppercorn and containing 1% to 2% less P₂O₅ than the earthy material. All transitions between the clayey and sandy phosphate are said to occur by Stutzer, who supposed that the former resulted from the disintegration of the latter. He figures sandy phosphate in which the larger particles appear to be 2 to 3 mm. in diameter, and also a section of oolitic phosphate composed of partly cemented grains, not over 1 mm. in diameter and with a concentric structure. Aso maintains that two kinds occur in quite separate parts of the phosphate field, and this is confirmed by the following observations of Rodgers, who states (1948) that the phosphate occurs in the northwest part of the island. This part consists of several basins separated by low ridges of coral rock. Two types of phosphate occur. The first kind consists of hard grains, red and brown in color but darker and much harder than those on Fais. It fills crevices between pinnacles and is associated with very little clayey material. The crevices are about 1.6 meters (5 feet) wide and 3 to 8 meters (10–25 feet) deep. This material is now almost exhausted. The second kind is a white clayey phosphate often showing traces of pisolitic structure which occurs under the swamps in the basins. At the edge it may be

1 meter or more (3–4 feet) thick and in the center at least five times as thick (15 feet or even more). Rodgers estimated that 400,000 tons of the white material remained in 1946 but states that the Japanese considered more to be present. The first analysis (I) is given by Elschner, repeated by Stutzer, the second (II) is also from Elschner. The other incomplete analyses (III and IV) were obtained by Rodgers in Japan and refer to material exported in 1940 and 1943, respectively.

	I ? Dry at 100°C.	II Dry	III	IV
H ₂ O	1.20%	1.90%	3.79%	4.99%
Organic matter	0.15	(ign. loss)	—	—
Total N	0.04	0.15	—	—
P ₂ O ₅	39.66	38.20	35.98	34.18
(Al,Fe) ₂ O ₃	1.57	1.70	2.21	2.70
CaO	51.52	52.70	—	—
MgO	—	0.46	—	—
F	tr.	0.80	—	—
CO ₂	—	2.60	—	—
SO ₃	—	0.48	—	—

Also indicates that the white earthy phosphate contains from 39.25% to 41.82% P₂O₅, the mean of three analyses being 40.69%, the brown oolitic phosphate 34.97% to 38.32%, the mean of three analyses being 37.10%. The earthy phosphate contained 0.80% to 1.61% (Al,Fe)₂O₃, the brown oolitic 1.80% to 2.20% (Al,Fe)₂O₃. Elschner says that from 3% to 6.5% CaCO₃ was present. The same author indicates the fluorine content to have varied from a trace to 1.25%. Sometimes whole cargoes contain phosphate with but a trace of the element. These low values are hardly confirmed by an analysis by Jacob, Hill, Marshall, and Reynolds (1933) who found 2.96% F in a sample containing 40.00% P₂O₅, giving a ratio F:P₂O₅ of 0.0740. This fluorine content and ratio are essentially the same as those of Ocean Island phosphate.¹

¹ Since the above was written, I have seen, through the kindness of the United States Geological Survey, a mimeographed report by Earl M. Irving and José Quema on the Angaur phosphate deposit. It appears that the phosphatized reef at Angaur is more or less coextensive with the area of the island, but that it is exposed or easily accessible only where it is not overlain by later reef rock, which covers the more peripheral parts of the island. The full account of this investigation, when it is completed and published, will be of great interest.

PELELIU OR PILILU ISLAND

LATITUDE 7° 01' N., LONGITUDE 134° 15' E.

A slightly elevated coral island, of maximum altitude 3 meters and of area about 21 km², north of Angaur. Also implies that the island has undergone several submergences and emergences. The central elevated area, presumably the Peleliu terrace of Tayama (1939), is much weathered and has a karstic appearance with sink holes. A residual mate-

rial rich in iron and alumina has collected in these depressions forming deposits of terra rossa in which brown pebbly phosphate occurs. This material contains:

	H ₂ O	P ₂ O ₅	(Al,Fe) ₂ O ₃
Fine (Aso)	1.51%	38.8 %	2.22%
Fine	0.94	38.43	2.67
Fine	1.26	37.82	5.63
Undesignated	1.42	37.04	6.99
Coarse	3.69	30.63	15.49
Coarse	2.68	33.37	11.65
Undesignated (Rodgers)			
1940	6.13	34.05	5.46
1940	18.35	19.90	14.54
1943	31.92	18.93	12.36

Also says that originally the reserve was set at 300,000 tons; later investigations suggested this figure to be excessive, but the most recent studies before the war indicate it to be of the correct order of magnitude. Statistics of the Japanese Ministry of Agriculture and Forestry, available to Rodgers, indicate that 107,875 tons were exported from 1937 to 1942. Owing to extensive military works on this island, it is doubtful if the deposits now exist in a recognizable condition.

EIL MALK OR MAKARAKU ISLAND

LATITUDE 7° 10' N., LONGITUDE 134° 18' E.

URUKTHAPEL OR URUKUTABURU ISLAND

LATITUDE 7° 15' N., LONGITUDE 134° 18' E.

Two islands of the Palau group north of Peleliu which appear to be volcanic peaks covered with coral; no volcanic rock is exposed. They are well wooded. According to Aso, phosphate occurs as lumps up to the size of a hen's egg scattered throughout terra rossa in basin-like depressions on both islands. The nodules are blue-black or white. The following analyses are given, those for Urukthapel being calculated on a water-free basis:

	H ₂ O	P ₂ O ₅	(Al,Fe) ₂ O ₃
Eil Malk:			
Pebbly phosphate	3.49%	28.74%	18.31%
Pebbly phosphate	3.10	32.86	4.27
Earthy phosphate	8.30	7.60	26.27
Earthy phosphate	4.57	16.78	23.50
Urukthapel:			
Nodular phosphate	—	32.77	13.97
Nodular phosphate	—	28.89	24.40
Earthy phosphate	—	13.38	40.21
Earthy phosphate	—	8.84	48.92

TOGOBEI, TOBI, LORD NORTH, NEVIL, KEDIL, OR
KODOGUBI ISLAND

LATITUDE 3° 03' N., LONGITUDE 131° 05' E.

A small island 2.4 kilometers long, surrounded by a drying reef. Its surface corresponds to the 1.5–2.0 post-Peleliu terrace (Tayama, 1939). It appears to be highly cultivated. According to Aso, the area of the island is about 624,000 m², of which 201,000 m² are covered with phosphate deposits. The phosphate is said to be on coral and foraminiferal sand, to be a scant meter thick, and to have no overburden. The total reserve appears to be of the order of 100,000 tons, but the beds have been much disturbed by irrigation and cultivation of the central area of the island. Statistics of the Japanese Ministry of Agriculture and Forestry, available to Rodgers, indicate that 25,486 tons were exported in 1937 to 1942. The upper part of the phosphate bed, 30 to 61 cm. thick, is a black earthy material (Aso, I, II, table 18) mixed with phosphatized coral and foraminiferal sand.

The middle part consists of a brown granular material (III, IV), the grains varying from the size of millet to that of rice seeds, and apparently composed of particles of phosphatized sand half a millimeter in diameter, of the same kind as are found in the upper earthy layer. At the bottom tuffaceous, ash-colored, brown, or blackish nodules, formed by the binding together of coral and foraminiferal sand of coarser diameter (1 mm.), have been largely phosphatized (V, VI), though often the inner core is of calcium carbonate, or has been dissolved out, leaving a hollow nodule.

Rodgers was given two analyses, of material obtained in 1940 and 1943, respectively containing 19.86% and 15.99% H₂O, 24.63%

and 24.70% P₂O₅, and 0.33% and 0.11% (Al,Fe)₂O₃.

The pH of extracts appears to be alkaline, from 7.0 to 7.6, whereas the Angaur phosphate gives slightly acid extracts from 6.2 to 6.4. The Peleliu oolitic phosphate is said to be slightly alkaline, 7.0 to 7.2.

From 85.6% to 92.1% of the Togobei phosphate is soluble in 2% citric acid; the corresponding figure for white argillaceous Angaur phosphate is 37.6%, while of Peleliu phosphate 26.4% to 61.6% of the P₂O₅ was soluble. When screened through a half-millimeter mesh the amount of citric-soluble phosphate was increased, 88.7% to 99.1% dissolving in 2% citric acid and 29.2% to 33.3% in neutral ammonium citrate. The corresponding figures for screened Peleliu granular phosphate are 56.8% soluble in citric acid, against 26.4% in the unscreened, and 6.1% soluble in neutral ammonium citrate. Aso thinks that the Togobei deposit is less ancient than that of Angaur and of Peleliu.

TABLE 18

	I	II	III	IV	V	VI
Loss at red heat	30.0 %	21.4 %	30.0 %	23.3 %	16.3 %	15.0 %
N	1.1	0.8	0.09	0.05	0.12	0.08
P ₂ O ₅	23.4	30.8	23.9	25.1	33.6	35.4
K ₂ O	0.05	0.07	0.01	0.01	0.07	0.04
CaO	41.4	49.0	51.0	51.7	51.4	51.5
(Al,Fe) ₂ O ₃	0.8	0.3	0.5	0.3	0.6	0.5
CO ₂	9.4	7.0	21.3	16.0	5.8	4.2

SONSOROL ISLAND

LATITUDE 5° 19' N., LONGITUDE 132° 13' E.

This and the adjacent islands of Panna, 2 kilometers to the north, and Puru (latitude 4° 40' N., longitude 131° 59' E.) to the southwest are small, low islands with rich vegetation. The islands have superficial phosphate deposits in their central parts. On Sonsorol the phosphate is about 15 cm. to 36 cm. thick and occupies an area of about 260,000 m², the estimated original reserve is 30,000 tons. On Panna the deposit is less extensive, the area being about 132,000 m² and the estimated reserve about 12,000 tons. The Puru deposit is supposed to consist of but 5000 tons. Statistics of the Japanese Ministry of Agriculture and Forestry, available to Rodgers, indicate that 18,000 tons were exported from Sonsorol in 1940 and 1941. The general nature of the phosphate on all three islands is similar to that of Togobei, earthy, sandy, and tuffaceous phosphate occurring. Aso gives the following analyses:

Rodgers obtained two analyses of Sonsorol phosphate in Japan:

	H ₂ O	P ₂ O ₅	(Al,Fe) ₂ O ₃
1940	21.12%	25.83%	0.28%
1943	29.07	24.01	0.18

ROTA ISLAND

LATITUDE 14° 09' N., LONGITUDE 145° 12' E.

The most important of the phosphate-bearing islands in the Marianas. As in the case of the other members of the group, to be discussed below, the volcanic core of the island is exposed. Though on Rota it is mostly covered with reef rock, Rodgers noted no exposure of volcanic rocks high enough to account for the presence in the phosphatic deposits of aluminum and ferric phosphates. The Marianas, though richly vegetated, are not so wet as the islands considered previously in this section. The interior of Rota forms a plateau which bears a peak rising to 497 meters. The slopes of the

	P ₂ O ₅	CaO	(Al,Fe) ₂ O ₃
Sonsorol			
Light brown earthy	31.87%	44.30%	0.43%
Dark brown sandy	30.78	42.29	0.70
Light brown tuffaceous	15.95	51.68	0.30
Brown tuffaceous	29.57	45.45	0.49
Black brown tuffaceous	36.27	49.80	0.23
Panna			
Dark brown earthy	22.63	48.62	0.26
Light brown nodular	21.13	52.00	0.30
Brown nodular	30.31	48.07	0.31
Puru (anhydrous)			
Weathered soil	29.66	37.01	0.20
Sandy	25.17	35.72	0.27
Exposed nodular	28.34	40.17	0.12
Exposed nodular	35.27	41.10	0.17

island are covered with reef rock and are marked by numerous terraces. Tayama (1939) distinguishes a doubtful terrace of the lower pre-Mariana series at the summit, i.e., *ca.* 500 meters, six terraces of the upper Mariana series at 480, 460, 420, 380, 300, and 260 meters, three of the middle Mariana series at 200, 180, and 140 meters, three of the lower Mariana series at 100, 80, and 60 meters, three of the Peleliu series at 40, 20, and 10 meters, and a post-Peleliu terrace at 3 to 4 meters. Aso indicates that the phosphate deposit lies in the highest part of the island. According to my friend Dr. Ethan A. H. Sims, who recently visited Rota, the phosphate workings lie at an elevation of at least 460 meters and on the highest elevated reef surface. Rodgers (1948) likewise indicates that the deposit lies on a plateau at about 458 meters. He describes the deposit as like that of Fais but perhaps with more clay and less shotty material.

Aso states that there is an area of 251,000 m² in which the phosphatic material is mixed with mud. The total reserve in the more restricted rich area, low in sesquioxides, is about 50,000 tons. The Japanese statistics available to Rodgers, however, indicate that 236,077 tons were exported in 1937 to 1944. The better material consists of fine granular, and also nodular, phosphate, usually low in sesquioxides, embedded in what Aso calls a phosphatic soil rich in sesquioxides. This latter material is supposed to be formed from a calcareous mud produced by the weathering of limestone and andesite.¹ On leaching, the ferric oxide and alumina are left as a fine deposit which can become phosphatized. In places nodular phosphate is exposed at the surface. The following partial analyses exist:

¹ Rodgers (personal communication) doubts this.

	P ₂ O ₅	Al ₂ O ₃
Nodular phosphate	37.40%	1.12%
Nodular phosphate	36.90	4.20
Fine-grained phosphate	36.00	7.70
Fine-grained phosphate	33.26	12.08
Phosphatic soil	25.61	39.40
Phosphatic soil	12.20	25.50

SAIPAN

LATITUDE 15° 15' N., LONGITUDE 145° 45' E.

This island has an andesitic core rising to an altitude of 400 meters. The rest of the island has a gently rolling relief and is largely used in cultivation of sugar cane. Tayama recognizes upper pre-Mariana terraces at 470 and 440 meters, middle pre-Mariana terraces at 350, 300, and 200 meters, a lower pre-Mariana terrace at 200 meters, middle Mariana terraces at 130 and 90 meters, lower Mariana terraces at 60, 40, and 30 meters, Peleliu terraces at 20 and 5 meters, and a post-Peleliu terrace at 1.5 to 2 meters. Aso states that about 100,000 tons of rock and earthy phosphate similar to that on Rota are available on the island at two localities, Marpi at the northern extremity, and Panaderu. Rodgers, who visited the former locality, says that it lay on a terrace about 15.3 meters (50 feet) above sea level, at the foot of the cliffs forming the western face of Mt. Marpi. The excavation has now been filled in, and nothing of the occurrence is visible. The Japanese statistics available to Rodgers indicate that 88,221 tons were exported between 1938 and 1944. As on Rota, the phosphate consists of nodular or powdery ore fairly low in sesquioxides mixed with a phosphatic earth high in sesquioxides. The following partial analyses are available, all but the last two being given by Aso:

	H ₂ O	P ₂ O ₅	(Al,Fe) ₂ O ₃
Red brown nodular	1.73%	36.69%	3.49%
White nodular	2.19	38.37	1.35
Selected granular	("usually anhydrous")	30.50	5.24
Phosphatic soil (? matrix)	6.20	15.18	37.65
Phosphatic soil (? matrix)	7.88	10.05	34.00
Saipan phosphate (Rodgers)			
1940	12.05	20.33	25.77
1943	9.04	19.80	29.67

TINIAN

LATITUDE 15° 02' N., LONGITUDE 145° 50' E.

Has a similar deposit at a locality called Marpo at the south end of the island and apparently at other places. Tayama (1939) indicates a possible lower pre-Mariana terrace at 175 meters, middle Mariana terraces at 170, 150, and 110 meters, lower Mariana terraces at 80, 60, and 45 meters, Peleliu terraces at 25 and 10 meters, and a post-Peleliu terrace at 1.5 to 2 meters. Rodgers saw a blueprint on Saipan showing the main deposit as lying in a basin just northwest of the highest point on the island, a flat-topped rock in the southeast part. This position suggests that the deposit lies on one of the Mariana terraces. Aso states that there are 2600 tons of material containing 30% P_2O_5 and 6000 tons of material containing 25% P_2O_5 . According to statistics available to Rodgers, 4000 tons were exported in 1941 and 1942. The following analyses are available; all but the last are given by Aso, but the meaning of the designations is far from clear:

	H ₂ O	P ₂ O ₅	(Al,Fe) ₂ O ₃
Above subsoil, near Lion Rock	12.09%	25.47%	16.48%
Above subsoil, Shiminato	14.45	10.13	28.02
Above subsoil, Marpo	6.65	33.35	4.01
Above subsoil, Marpo	14.69	23.63	15.55
Ore, Marpo	3.53	36.23	0.86
Tinian phosphate, 1943 (Rodgers)	25.37	17.95	16.16

AGUIJAN OR AGIGUWAN ISLAND

Just southwest of Tinian, is said to have a thin coating of phosphate on the surface limestone and a more extensive deposit of phosphate clay. Aso states that 30,000 tons of material containing 20% P_2O_5 and 18% (Al,Fe)₂O₃ exist on the island. Rodgers indicates that the deposit is on the flat plateau at about 60 meters (200 feet or so) which constitutes most of the island. Tayama records middle Mariana terraces at 180 and 160 meters, lower Mariana terraces at 80 and 45 meters, Peleliu terraces at 30 and 10 meters, and a post-Peleliu terrace represented by a raised notch. It appears from Rodgers' account that the deposit must lie on lower Mariana depositional surfaces.

MEDINILLA OR BIRD ISLAND

LATITUDE 16° 00' N., LONGITUDE 146° 00' E.

Suspected by Aso to bear phosphatic guano as there are said to be places where birds congregate. The island is stated to be flat and barren ("Pacific islands pilot," United States Hydrographic Office, 1920a), but Aso says that shrubs grow thickly and that there are grassy plains. It must be regarded as a very doubtful phosphatic island.

MARCUS ISLAND

LATITUDE 24° 14' N., LONGITUDE 154° 00' E.

An elevated triangular atoll situated on a reef platform of mean width about 200 meters. The maximum length of the island is about 2.9 kilometers. The island reaches an elevation of about 23 meters at the northern point which bears six strand lines. There is evidently a considerable amount of elevated reef coral *in situ* in the interior of the island. Four depressions filled with black alluvial soil represent the old lagoon.

The island is well wooded, *Tournefortia* being the most important tree. Coconuts of great age were observed by Bryan in July, 1902, though the island had not been regularly visited from Japan until late in the nineteenth century. Ten species of vascular plants were also noted by the same observer. The density of the vegetation and the fact that Japanese bird hunters obtained all their water from rain suggest a moderate precipitation. Bryan believed that the failure of cultivated bananas to bear fruit was owing to insufficient moisture.

The avifauna was rich prior to the colonization of the island by the Japanese. The colonists came in search of guano, but finding none "by their crude methods" they killed and converted to fertilizer the entire

colony of *Diomedea immutabilis* and *D. nigripes*. *Sterna fuscata*¹ occupied a belt on the upper beach all around the island. The eggs and young occupied every square yard of this area, and the size of the colony is indicated by the fact that the Japanese killed 50,000 a year for plumes. Bryan thought that some hundred thousand birds would be a conservative estimate of the numbers.

Noddies, *A. stolidus*, nested in trees farther back from the shore, but the number of birds was only about one-tenth that of the sooty terns. The forested interior also provided nesting sites for smaller numbers of *Anous minutus marcusii* (Bryan) and *Gygis alba*.

Thousands of *Sula leucogaster* (sub *S. sula*) were found in colonies under the trees at the top of the beach. *S. dactylatra* and *S. s. rubripes* are evidently much less common. A colony of *Fregata minor* (sub *aquila*) exists mainly on the food captured by the brown boobies.

The sole indication of phosphatization given by Bryan is contained in a footnote to his paper: "Mr. Sedgwick . . . made a number of excavations in various parts of the island, but especially in the bottoms of these old lagoons, which were now overgrown with thick grass, shrubs and trees, over which towered fine coconuts of great age. In these depressions exist varying conditions in the under strata, though the surface is uniformly composed of alluvial deposits, varying in thickness from eight to fourteen inches. Underneath this, in the coconut patch, were found coral sand and earth from six to ten inches, then a layer of coral sand with pebbles, and occasionally solid base-forming coral in a slab, under which was found broken coral. In the two other larger alluvial patches beneath the black earth was light clay-colored mud composed of fine particles of coral, and below this were larger pieces of coral as far down as the excavations were carried, which was from six to eight feet. The investigations of the Chemist were not nearly as complete or as conclusive as it had been planned to make them. A limited quantity of guano was found which gave a test of 70 per cent phosphate of lime; but the great

majority of the samples secured were not so flattering."

In spite of the apparent paucity of phosphatic material on Marcus Island indicated by this account, it appears from Aso (1940) that a considerable amount of phosphate has been found on the island. Two kinds of phosphate are recorded. One kind (I) is said to be black, powdery, and containing much decaying plant remains. This appears to be a phosphatic soil and may have been formed by the modern bird colony. The other kind (II) is granular, like that of Togobei, and is evidently mixed with lumps of coral. The following analyses are given:

	I	II (Coral screened out)
H ₂ O	18.03%	10.25%
Loss on ignition	41.13	13.82
Insol. in HCl	0.09	0.22
Total N	2.50	0.54
P ₂ O ₅ total	14.13	31.02
P ₂ O ₅ sol. in 2% citric acid	5.04	22.25
CaO	21.66	37.16

According to Aso, 6113 tons of phosphate were removed from the island between 1907 and 1920. The island was administered by the Japanese as part of the Bonin group and is the source of Bonin guano recorded by Meise.

PHOSPHATIZED ISLANDS IN THE BORODINO AND RIU KIU GROUPS AND OTHER LOCALITIES SOUTH OF JAPAN

The last group of Pacific islands to be examined lies north of the preceding, and the islands themselves may be best considered as two subgroups. The two Borodino or Daito Islands that bear phosphatic deposits are entirely composed of limestone save for beds of drifted pumice and the phosphatic materials of avian origin. The Riu Kiu Islands have had a more complex geological history and are not oceanic islands.

THE BORODINO OR DAITO ISLANDS

Of the three islands comprising this group, two, Kita Daito Jima, or North Borodino, and Okino Daito Jima, or Rasa Island, had very large phosphate deposits which originally rivaled those of all but the most productive of the phosphatic islands. Minami

¹ Subspecific determinations of a number of Marcus Island birds appear to be doubtful.

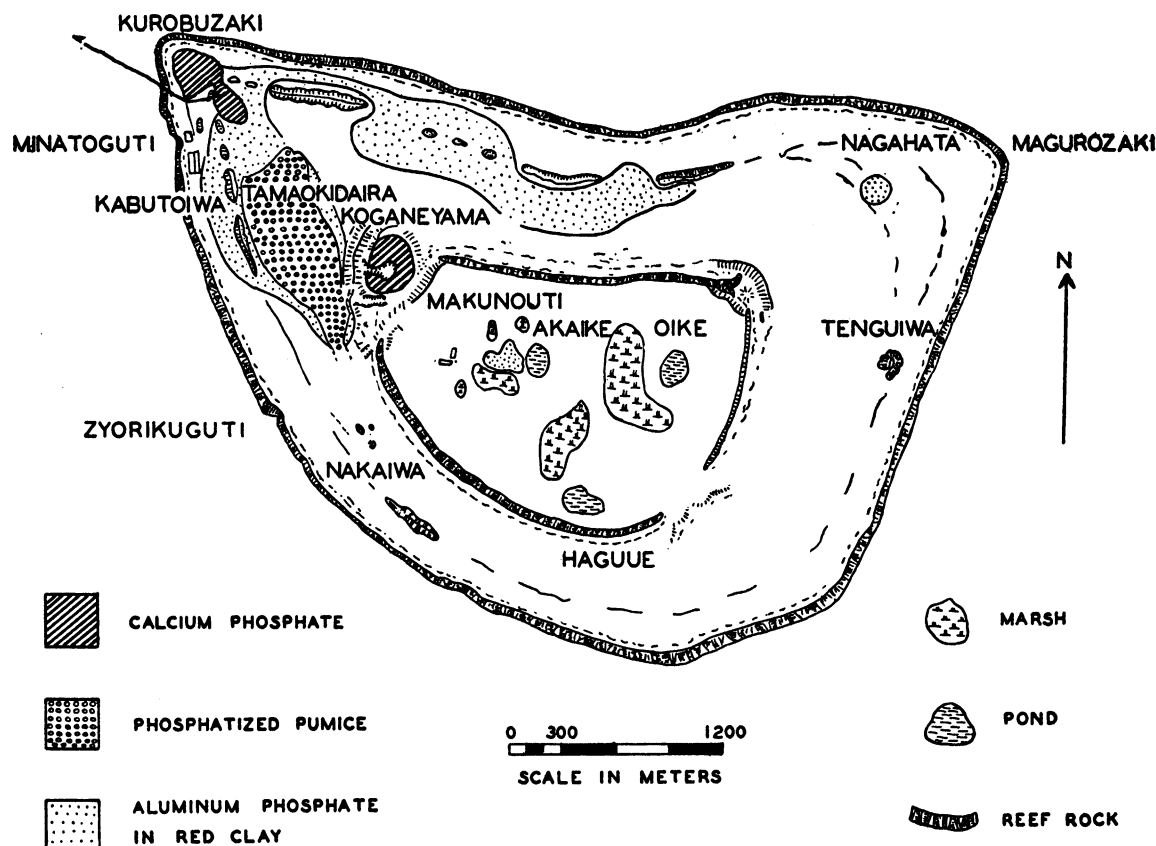


FIG. 63. Map of Kita Daito Jima. After Yamanari.

Daito Jima, or South Borodino Island, appears to lack phosphatic deposits of any importance.¹ The deposits on the two phosphatized islands are undoubtedly ancient, but it appears from the account given by Yamanari (1935) that a limited colony of the now extinct albatross, *Diomedea albatrus* Pallas, occupied the island, particularly around its northwestern point, Kurobuzaksi, prior to 1919. This bird apparently favored shores facing the predominant northwest wind, as it was said to be unable to take off unless a wind is blowing.

In their natural state both the islands were quite heavily vegetated. Small fresh-water lakes occur on Kita Daito Jima, and the rainfall is evidently high.

KITA DAITO JIMA, KITA OAGARI JIMA, OR
NORTH BORODINO ISLAND

LATITUDE 25° 57' N., LONGITUDE 131° 17' E.

Perhaps the best known and at the same

¹ Cf., however, Nugent (1948).

time the most complicated of the phosphatic islands of the world. It is a semicircular island about 4.8 kilometers long with an area of 13.3 km² and a maximum elevation of 71 meters (fig. 63). The north side corresponds to the diameter of the semicircle and is slightly concave. The coast line is marked by a modern bench and a cliff. The central part of the island forms a basin known as Makunouti which is completely surrounded by higher ground. The slopes facing the basin form cliffs, particularly on the south, and several swampy areas occur within the basin. Two of these lakes, Aka-ike and O-ike, have been studied by Yoshimura (1938), who finds their water to be slightly acid (pH=6.4) with some chloride (Cl 104 and 141 mg/1) of marine origin, sodium (52.5 and 71.4 mg/1) being the chief cation. Calcium was fairly low (12.3 and 12.4 mg/1). The water was fairly rich in organic matter and in plankton (Uéno, 1938) and is characterized as intermediate between dystrophic and eutrophic. The sediments contain much

coarse detritus derived from land plants. It is clear that the character of the lakes is dependent more on the presence of the rich vegetation than on the calcareous bedrock of the islands. The coastal plateau between the basin and the sea cliff is called Hagu-ue. In places it bears an intermediate line of hills between the coastal cliffs and the cliffed hills marking the boundary of the interior basin, suggesting a double rampart structure. In the northwestern part of the island a rather extensive second basin, called Tamaokidaira, with a floor at an altitude of about 40 meters, is enclosed by these outer hills and by the highest hill of the island termed Koganeyama, which is part of the interior rampart around Makunouti. This second basin is entirely enclosed, but on its northwest side the enclosing wall rises only slightly above 45 meters. This fact is of some importance in understanding the history of the main phosphate deposit which lies in Tamaokidaira. Apart from residual deposits and phosphate, the island is composed of limestone. The exposed beds are designated Daito limestone. A boring (Hanzawa, 1938) made in the northern part of the central basin exhibited the following section:

ZONES	METERS	
1	0-103.5	Indurated dolomitized limestone containing 17.03%-18.03% MgO <i>Acervulina inhaerens</i> Schultze abundant in upper part, <i>Amphistegina radiata</i> (Fichtel and Moll) abundant in lower part
2	103.5-116.4	Calcareous grayish blue mud with a granular porous limestone layer at 107.2-109.8 meters <i>Cardium fragum</i> Linnaeus numerous, Foraminifera as in zone above
3	116.4-209.3	Porous pure limestone containing 0.63% MgO Various Foraminifera including <i>Miogypsina polymorpha</i> Rutten and <i>Nephrolepidina tournoueri</i> Lemoine and R. Douvillé
4	209.3-395.0	Coarse-grained calcareous sand Various Foraminifera, including <i>Nephrolepidina tournoueri</i>

5 395.0-431.7 Fine-grained calcareous sand
Miogypsinella borodinensis Hanzawa (? *nomen nudum*)

Zones 4 and 5 are certainly Aquitanian; zone 3, Aquitanian or Burdigalian. Zone 1 is referred by Hanzawa to the Plio-Pleistocene; all the Foraminifera occurring in it are of recent species. A large tooth of *Carcharodon megalodon*, described as *C. m. yamanarii* Yabe and Sugiyama (1935), has been obtained from the Daito limestone of the northeastern part of the island. A small molluscan fauna is also present in the limestone exposed on the island. Nomura and Zinbô (1935), who have described this fauna, note that all but one of the species recorded still inhabit the adjacent seas; the sole exception is *Terebralia gourmyi* (Crosse), a living species of gastropod hitherto known only from the Malayan region. Yabe and Sugiyama consider the exposed part of the Daito limestone to be "latest Pliocene? or more probably Pleistocene." Nomura and Zinbô regard it as nearly contemporaneous with, or even somewhat younger than, the Riu Kiu limestone, which they think is more probably Lower Pleistocene than late Pliocene.

Analyses of the limestone by Yamanari (1935)¹ are given here in table 19. Analysis IV (table 19) from zone 1 presumably indicates the kind of material from which the red clay, described below, has been derived as a residual product of weathering.

The most complete account of the superficial deposits of the island is given by Yamanari (1935).

The dolomitic Daito limestone is very porous and full of cavities, in part representing internal casts of shells. In its lower part the cavities are apparently empty. Tide water may enter them and on retreating set up a negative pressure which tends to draw superficial ground water downwards and so into the ocean. The surface of the limestone is dissected into pinnacles. Above the shore line, at a level occasionally reached by waves generated by typhoons, the pinnacles can be observed as superficial features of the

¹ I am immensely indebted to Dr. John Rodgers for a translation of this work, by Teruhiko Hirasawa.

TABLE 19

	I	II	III	IV	V	VI
Ign. loss	45.78%	45.95%	44.32%	46.86%	46.36%	44.31%
CaO	32.50	33.25	50.18	35.50	34.55	55.25
MgO	18.23	18.74	4.47	17.03	18.03	0.63
SiO ₂	1.45	0.40	0.25	0.16	—	—
Fe ₂ O ₃	0.18	0.36	0.10	0.08	—	—
Al ₂ O ₃	0.48	0.42	0.17			
P ₂ O ₅	1.18	0.63	0.30	0.16	0.16	0.05

I. "Slack limestone."

II. Bedrock of phosphate ore.

III. Minatoguchi on the northwest coast.

IV. 7.21–7.31 meters in boring zone 1.

V. 53.75–53.54 meters, zone 2.

VI. 127.87–130.98 meters, zone 3.

landscape, but inland the spaces between them are filled with a red or brown residual clay comparable to the terra rossa of the Mediterranean region. In the northwestern Tamaokidaira basin there is also a superficial deposit of a pumiceous clay, to be discussed at length below. The deepest pot-hole-like depressions in the Tamaokidaira basin may widen about 10 meters below the surface to form large caves in which clay and phosphate have been deposited. No stalactites or stalagmites appear to project into the cave filling, and Yamanari raises the question as to whether the caves have been formed by chemical erosion by ground water moving downward or by solution below

water level. Ordinarily the clay-filled cavities between the pinnacles are not more than 5 meters deep, but in the central depression some may be 10 meters deep, and in the Tamaokidaira basin the deepest depressions are 40 meters deep, extending to modern sea level. The filling of all the deeper cavities appears to have been washed in from above. Bird bones, said by Aso¹ to have been identified as those of albatrosses, have been noted in such deposits. The red or brown clay oc-

¹ Aso also says plumage has been found in the deposits. This seems very unlikely unless both the bones and feathers that he noted actually belonged to a recent albatross that had died on the island and become accidentally associated with phosphate.

TABLE 20

	I	II	III	IV	V
Moisture	9.41 %	6.53 %	3.90 %	6.47 %	5.22 %
Ignition loss	13.776	13.459	8.117	12.638	11.943
Total N	0.404	0.157	0.181	0.178	0.092
Insol. residue	49.123	42.206	66.820	43.418	32.759
SiO ₂ sol. in HCl	0.381	0.370	0.058	0.141	0.688
SiO ₂ sol. in Na ₂ CO ₃	11.891	9.115	10.973	10.781	8.264
Al ₂ O ₃	2.042	5.617	5.123	16.315	18.855
FeO	7.828	15.587	2.862	6.966	4.961
Fe ₂ O ₃	7.904	6.852	2.247	2.534	1.992
MnO	0.708	0.742	0.797	0.066	0.067
CaO	1.355	1.084	0.844	2.017	5.623
MgO	0.743	0.418	0.396	0.507	0.497
K ₂ O	0.219	0.372	0.187	0.477	0.667
Na ₂ O	0.117	0.188	0.185	0.158	0.215
P ₂ O ₅ [sic]	2.098	2.676	1.381	4.106	11.954
SO ₄	0.200	0.125	0.148	0.345	0.625
Clay, sol. in H ₂ SO ₄	Al ₂ O ₃	10.563	15.349	5.184	10.833
	Fe ₂ O ₃	2.825	2.501	1.275	1.464
	SiO ₂	12.898	15.024	7.640	15.401

curing throughout the island contains no particles larger than 2 mm. in diameter, and usually at least 88% of it consists of particles less than 0.01 mm. in diameter. When dried in air it crumbles. It is easily dispersed in water but settles immediately. During heavy rain, water runs off the red clay surface, but, as soon as the rain stops, the surface of the clay becomes free of water, the water soaking into the clay and the excess being taken up by the cavities in the limestone below. This permeability of the clay to water is in marked contrast to the properties of the pumiceous clay which gives a special character to the Tamaokidaira basin. The red clay throughout the island is more or less phosphatized, but the phosphate content is in general higher in the clay on the Hagu-ue plateau than in that of the central depression. It seems possible that the phosphorus of the clay poorest in the element is a residual material like the iron and alumina with which it is associated. The analyses in table 20, given by Yamanari, relate to:

- I. Western part of central basin, Makunouti, superficial.
- II. Western part of central basin, Makunouti, deep.
- III. Central part of central basin, Makunouti, superficial.
- IV. Central part of central basin, Makunouti, deep.
- V. Hagu-ue plateau, superficial.

Owing to the importance of the locality and the inaccessibility of Yamanari's report, the analyses are given just as they stand (table 20), though their interpretation is obscure.

In certain parts of the island masses of

aluminum phosphate, usually of diameter less than 20 cm., are found scattered through the red clay. Such masses occur in the central basin, around Daizingu-yama, in the plateau of the northwest part of the island, and around the main phosphate deposit in the Tamaokidaira basin. A profile through the red clay found in the latter region, but not associated with the pumiceous clay characteristic of Tamaokidaira, is given by Yamanari in diagrammatic form:

METERS

- 0.3 Soil
- 1.0 Reddish brown homogeneous clay, with recent plant roots
- 1.0 Humified gray homogeneous clay, with recent plant roots
- 2.2 Reddish brown homogeneous clay, with recent plant roots
- 0.1 Black layer with carbonized wood
- 3.0 Reddish brown homogeneous clay with white aluminum phosphate in lower third
- <0.1 Black manganiferous coating
- (Bedrock) Dolomitic limestone

Analyses of the white aluminum phosphate forming more or less pure masses as given by Yamanari are at the bottom of this page.

In addition to such material and to the phosphatized pumiceous clay found in the Tamaokidaira basin, isolated masses of calcium phosphate are found in the highest hill of the island, Koganeyama, and near the northwest point, Konebusaki, and in some caves in the Tamaokidaira basin. No adequate accounts of these occurrences have been given. Aso says that it may be either powdery or an agglomerate mixed with clay, filling pockets in the coral. He estimated that the

	I	II	III	IV	V
Ign. loss	47.27%	46.48%	41.72%	36.46%	—
SiO ₂	1.21	9.20	29.68	40.00	23.84%
Al ₂ O ₃	44.78	42.13	39.23	33.61	26.55
P ₂ O ₅	51.46	39.20	19.50	13.74	25.34
Fe ₂ O ₃	0.88	3.85	7.74	10.00	10.15
CaO	1.38	4.40	3.22	1.94	5.40

- I. Highest grade phosphate.
- II. High grade.
- III. Medium grade.

- IV. Low grade.
- V. Brown clay with highest grade ore.

calcium phosphate deposit on Koganeyama covered 66,000 m², and gave the following partial analyses:

P ₂ O ₅	(Al,Fe) ₂ O ₃
38.15%	2.17%
37.29	4.88
36.22	4.47
32.26	17.92
25.12	6.46

By far the most important phosphatic material on Kita Daito Jima is associated with a deposit of pumiceous clay in the Tamaokidaira basin. This deposit lies on the top of a material which represents the ordinary red clay of the fissures between pinnacles in the rest of the island, and if it were removed the general nature of the basin would differ little from the central interior depression. The origin of the pumice (Oinouye, 1928; Yamanari, 1935) must have been a submarine eruption, as the island shows no sign of volcanic activity, and the particles of pumice found on the island are all water worn. Yamanari notes that considerable quantities of pumice have been observed floating on the surface of the sea after recent eruptions. He suspects that at the time of such an eruption the island lay about 40 meters lower than it does today and the Tamaokidaira basin contained a shallow lake in which water plants were growing. A typhoon then cast the pumice against the sides of the island, pounding much of it to silt and finally throwing most of it over the rampart into the lake basin. Here the coarser part of the material sedimented mechanically; the finer part flocculated. A layer of pumiceous clay was deposited: the basal bed, dark yellowish in color, being coarser with little colloidal material; the middle bed, generally a soft grayish purple clay, largely colloidal; an upper bed the same consistency and color as the middle but with less colloidal material than the middle is supposed to be due to disturbance of the lake bottom. It may be perhaps suggested that rain subsequently washed some of the coarser material deposited on the seaward slope of the basin into the lake. In some places the pumiceous clay is separated from the underlying red clay by phosphatic material replacing the roots of plants; in other places the junction between

red and pumiceous clay is more gradual. A bird colony appears to have existed in the basin prior to the delivery of the water-worked pumice, as Yabe and Sugiyama have described exotic pebbles, which can hardly be anything else but the gizzard stones of birds, from the red clay below the pumiceous clay.

These deposits of the Tamaokidaira basin are strongly phosphatized. Where the pumiceous clay is separated from the red clay by the root layer the phosphatization is confined to the pumiceous clay, and the root layer and the red clay below are more or less unphosphatized. Where the root layer is absent the red clay is phosphatized to a great depth (fig. 64).

The phosphatic material is divided into two parts by Yamanari; the upper or A ore-body consists of ferric aluminum phosphate, the lower or B ore-body of aluminum phosphate and aluminosilicate clay. The upper A body consists of three different rocks:

1. Root phosphate lying in two layers, a narrow one above and a thicker but less phosphatized one below the basal bed of pumiceous clay. Below the lower root phosphate the red clay is relatively unphosphatized.

2. Reticulated phosphate, a reddish brown or light gray material which appears to consist of earthy lumps, but which when weathered shows a reticulate structure.

3. Hard phosphate, white, brown, chocolate, gray, or grayish green, for the most part below the reticulated phosphate, containing scattered foreign pebbles, presumably gizzard stones as described above.

Analyses of these materials are given (table 21), but it is not clear if the compact phosphate of the analytical table corresponds to the hard phosphate and the vesicular to the reticulate.

Ferrous iron was determined in four samples, of which at least the last is the same as I in table 21:

	Fe ₂ O ₃	FeO
Brown vesicular	22.12%	0.15%
Pale green vesicular	22.42	0.38
Chocolate	18.85	0.26
Pale green, compact	1.50	0.38

Two other analyses, apparently on a water-free basis, are as follows:

	I	II
Al ₂ O ₃	25.27%	34.13%
P ₂ O ₅	44.40	47.43
SiO ₂	8.92	7.04
Fe ₂ O ₃	18.44	8.06
CaO	1.74	1.84
TiO ₂	0.62	1.13

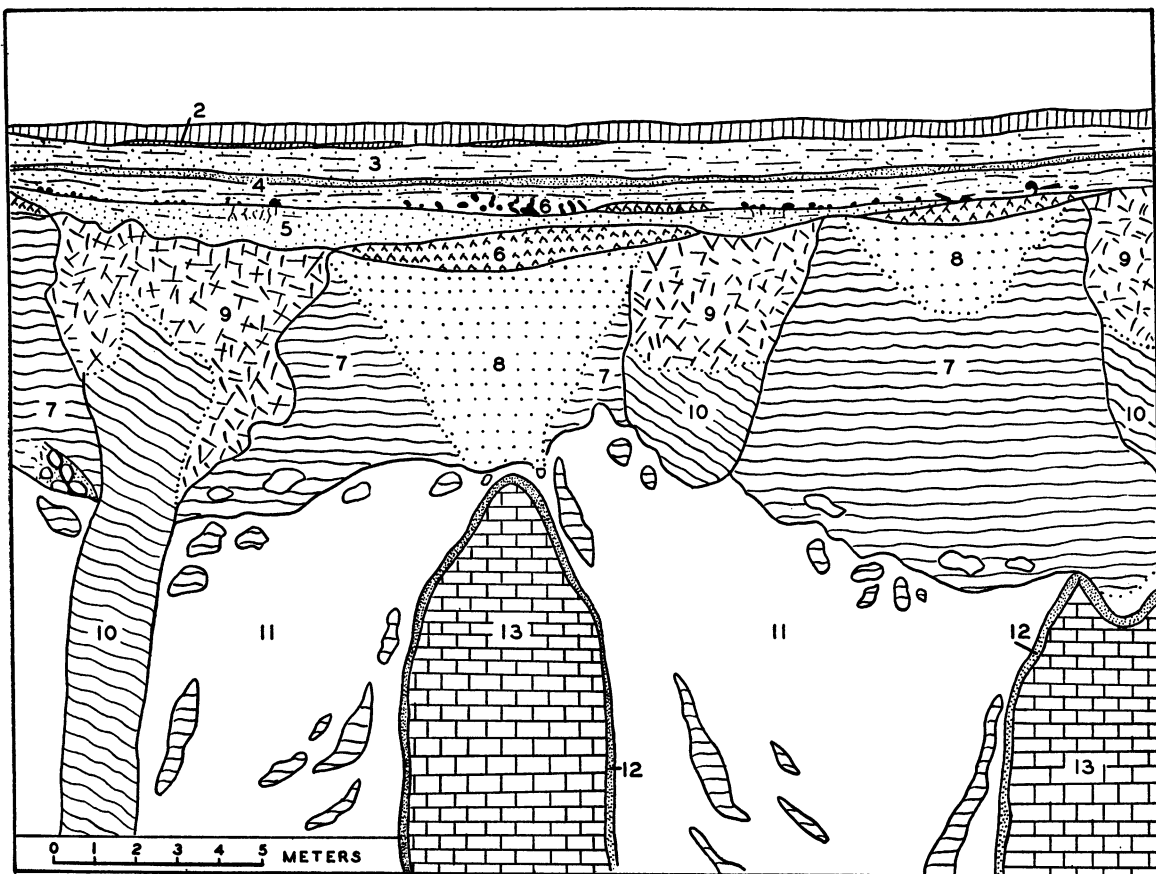
I. White, kaolin-like, compact.

II. Gray, compact.

The first is supposed to represent coprecipitation of aluminum and ferric phosphate by

electrolytes, the second to represent isoelectric precipitation of aluminum phosphate and ferric hydroxide.

The lower B ore-body, lying 5 to 20 meters below the surface, is distinguished from the A ore-body primarily by its lower iron and higher silica content. Four main types, α , β , γ , and δ , of material are distinguished by Yamanari, differing progressively in their silica content. The pure end members α and δ , corresponding to aluminum phosphate and aluminum silicate, are white. The main mass



1. SOIL
2. THIN LAYER OF FERRIC ALUMINUM PHOSPHATE
3. UPPER BED 4. MIDDLE BED 5. BASAL BED
6. ROOT PHOSPHATE OR CONCRETIONAL FERRIC ALUMINUM PHOSPHATE
7. CLAY WITH PUMICE
8. PHOSPHATIC BROWN CLAY
9. RETICULATED FERRIC ALUMINUM PHOSPHATE
10. HIGH GRADE HARD FERRIC ALUMINUM PHOSPHATE
11. SOFT ALUMINUM PHOSPHATE
12. BLACK MANGANIFEROUS COATING
13. LIMESTONE

FIG. 64. Section of phosphatized pumice, Kita Daito Jima. After Yamanari.

having a range of composition denoted by β , however, is full of brown spots. Apparently the material expands and contracts with hydration and dehydration and when contracted it has cracked, allowing brown clay from above to be washed in by rain water. The analyses given in table 22 indicate the composition of these types.

α , γ , and δ varieties lost water at different vapor tensions and temperatures very much as do wavellite crystals. Some crystalline material surrounded by earthy phosphate, from the reticulated phosphate of the upper A ore-body, had a composition comparable to wavellite, but a rather lower refractive index (1.48 as compared with 1.54). It is

TABLE 21

	I	II	III	IV	V	VI	VII	VIII
Ign. loss (i.e., mainly H ₂ O)	25.14%	21.88%	8.10%	21.08%	21.57%	12.66%	15.00%	19.18%
Al ₂ O ₃ , on dry basis	39.54	16.08	27.49	25.31	21.63	21.85	21.84	24.56
P ₂ O ₅ , on dry basis	55.59	48.00	47.18	44.18	42.66	41.91	39.21	30.65
SiO ₂ , on dry basis	1.79	2.75	2.00	15.00	5.13	12.26	[9].71*	19.16
Fe ₂ O ₃ , on dry basis	1.50	32.10	18.85	14.00	26.73	22.42	24.12	17.53
CaO, on dry basis	0.75	—	0.27	—	1.29	0.80	1.53	4.77
MgO, on dry basis	0.29	6.18	—	0.33	0.32	—	—	0.32
CO ₂ , on dry basis	0.12	0.04	—	0.14	0.15	—	—	0.30
SO ₄ , on dry basis	—	—	—	—	0.32	—	—	0.19
K ₂ O, Na ₂ O, on dry basis	—	—	—	—	1.06	—	—	2.57

- I. Pale green, compact.

II. Pale green, vesicular.

III. Gray, compact.

IV. Gray, vesicular.
- V. Brown, vesicular.

VI. Gray, vesicular.

VII. Vesicular, with red clay.

VIII. Root phosphate, with red clay.

* The digit before the decimal point is defective in the original. The sum of this column is given as 96.20, whereas without the SiO₂ it should be 86.70. The missing digit is presumably 9, although subtraction gives 9.50 rather than 9.71.

When the phosphate is mined very fast, the freshly exposed surface at the bottom of the ore face or in caves running horizontally from the depressions between pinnacles is seen to consist of a semitransparent gel. This material may form scale-like structures (fig. 65). The following analyses of such material are given:

	I	II	III	IV
H ₂ O	38.12%	52.06%	74.79%	74.34%
SiO ₂	45.49	48.60	51.59	32.91
Al ₂ O ₃	51.39	49.46	35.69	52.65
P ₂ O ₅	2.48	1.86	5.68	13.56
CaO	0.19	—	6.29	0.37

- I. Pulverulent incrustation, dry cave.
- II. Glassy gel, dry cave.
- III. Milky white gel, wet cave.
- IV. Wine-colored gel, wet cave.

A series of dehydration experiments made by Yamanari seem to indicate that the

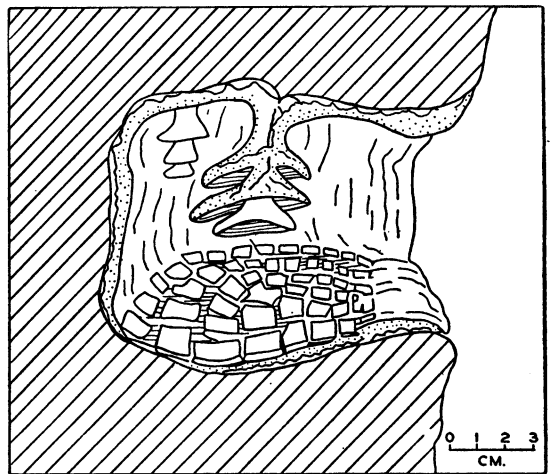


FIG. 65. Scale-like formation of semitransparent gel in cavity, Kita Daito Jima. After Yamanari.

TABLE 22

	SiO ₂	Al ₂ O ₃	P ₂ O ₅	Fe ₂ O ₃	CaO
Type α					
Pale green, compact	1.79%	39.54%	55.59%	1.50%	0.75%
White clayey	1.10	45.00	51.25	1.25	1.11
White clayey	0.18	48.15	50.42	0.70	0.60
White clayey	0.23	50.36	47.90	—	—
White clayey	1.09	51.09	46.98	1.43	1.14
White clayey, pale gray tint	1.84	52.55	44.61	1.29	3.60
White clayey, pale gray tint	2.22	45.23	36.08	—	15.93
White clayey, pale gray tint	2.56	43.44	42.07	2.33	6.04
White clayey, pale gray tint	2.90	43.10	35.10	1.30	13.80
Brown spots in white clayey matrix	4.53	50.65	44.07	1.89	1.32
	5.25	49.98	39.01	3.20	6.13
	5.76	42.53	40.69	5.89	5.09
	6.06	41.67	36.12	3.21	10.69
	6.40	44.80	39.45	4.22	4.00
	8.43	44.80	35.67	2.43	7.88
	10.73	43.61	33.15	4.01	6.79
	11.93	40.64	34.24	7.26	7.36
	12.48	44.52	31.69	1.73	5.23
	15.80	41.59	26.64	2.81	6.33
	16.14	43.33	30.28	4.26	7.39
	17.56	39.20	29.90	5.20	4.81
	18.15	39.20	26.21	1.87	8.82
	19.90	42.83	24.50	0.90	7.00
Type β	20.80	44.20	24.10	2.10	3.50
Mottled ore white and brown	21.03	43.28	23.33	2.65	4.57
	22.71	40.65	21.55	3.00	4.06
	23.45	42.03	24.28	4.66	3.74
	26.45	44.70	24.67	1.60	1.03
	30.22	42.88	18.67	2.40	1.80
	32.50	45.76	20.07	—	—
Type γ	33.04	42.28	17.29	2.37	4.12
Resinous when wet, white, earthy	35.76	49.76	13.30	—	1.23
when dry	38.18	46.32	12.69	—	1.83
	40.13	47.69	9.26	0.52	9.26
Type δ	40.22	44.90	6.72	0.22	1.83
White, earthy	50.66	42.78	5.45	—	1.10

obvious that no further progress in the study of the Kita Daito Jima phosphate is possible without X-ray diffraction spectrography.

Yamanari believes that the phosphatization has involved isoelectric precipitation of oppositely charged colloidal particles, in the manner that Mattson supposes occurs in soils. Coprecipitation of negatively charged aluminum phosphate and positively charged alumina would give the α type of the lower deposit in which there is an excess of Al₂O₃ over P₂O₅. Coprecipitation of silica and alumina would give the δ type, and the intermediate β and γ types are formed by coprecip-

itation of appropriate intermediate mixtures. A red gel found at the base of the deposit may represent the precipitation of silica sol by ferric hydrate sol, while the material given in analysis II on page 242 is supposed to be due to precipitation of aluminum phosphate sol by ferric hydrate. The pH values of the medium in which such precipitations occur can be calculated from Mattson's data and are found to be for the materials of the B ore-body between 5.20 and 6.80.

The calcareous varieties, and some varieties (e.g., I on p. 242) in which both ferric and aluminum phosphates occur, are sup-

TABLE 23

	I	II	III	IV	V	VI	VII	VIII
Ign. loss (H ₂ O)	14.84%	16.26%	13.57%	14.63%	7.48%	16.03%	18.48%	26.5 %
Al ₂ O ₃	12.04	16.81	12.68	9.74	11.37	18.12	29.94	27.33
P ₂ O ₅	1.01	23.05	21.03	8.05	4.37	12.75	15.04	25.80
SiO ₂	72.23	38.75	48.64	69.75	69.88	39.89	26.85	17.89
Fe ₂ O ₃	2.17	13.83	11.29	9.63	5.34	18.85	15.56	4.81
CaO	—	2.74	2.27	1.96	1.45	3.48	5.70	—
MgO	0.30	0.26	—	0.48	0.28	0.17	0.32	—
CO [<i>sic</i>]	0.50	0.17	—	0.12	0.15	0.16	0.39	—
K ₂ O, Na ₂ O, CaO	10.19	2.99	—	1.91	6.81	4.52	4.93	—

I. Pumice of hypersthene andesite near bedrock in middle of basin.

II. Pumiceous clay.

III. Pumiceous clay.

IV. Mixed pumiceous and red clay from 15 feet (translation *sic*).

V. Mixed pumiceous and red clay, southern part of basin, 12 feet.

VI. Red clay in contact with IV.

VII. Red clay 15 feet below V.

VIII. Red clay 15 feet below IV.

posed to be due to precipitation by electrolytes. This interpretation may not be exact in its details, but the presence of much obviously colloidal matter suggests that movement of sols and coagel formation has played an important part in the history of the deposit.

Yamanara gives analyses of the least phosphatized materials, here reproduced in table 23.

In phosphatization of pumice as represented by I, to give material comparable to II or III more silica is lost than phosphate is gained. The silica must have migrated downward, and its loss is due in part to processes other than phosphatization. Yamanari supposes that the humic matter of the lake bottom facilitated this loss of silica. Much of this silica has been completely lost,

but some of it is represented by the δ type of colloidal material of the B ore-body. Though the B ore-body contains on a dry basis more aluminum than the red clay, its water content is high, and in a natural wet state unit volume of the B ore-body contains about as much aluminum as dry red clay. It is therefore reasonable to suppose that the aluminum of the deeper deposits is derived from the red clay altered *in situ*. The iron content decreases markedly with depth. This is attributed to variation in water level, iron forming below the ground water level and later, as the latter rises, becoming oxidized and producing a ferric hydrate sol that may further migrate upward by capillary action. The process is compared to iron pan or ortstein formation. In the central basin of Kita Daito Jima a normal iron pan has been found.

TABLE 24

	White	White	White	White	Red	Red	Red	Red
H ₂ O	17.54%	17.68%	23.33%	10.50%	10.76%	6.78%	10.39%	12.40%
P ₂ O ₅	36.74	37.97	29.41	32.00	33.43	28.99	26.54	32.53
Sol. P ₂ O ₅	15.92	16.54	—	—	11.36	10.51	—	—
Al ₂ O ₃	24.52	23.71	37.38	26.02	17.85	12.22	17.19	16.80
Fe ₂ O ₃	5.20	6.60	2.80	15.27	13.76	15.50	13.5	26.60
Calcium	0.72	tr.	—	—	4.01	1.10	—	—
Magnesium	0.25	1.10	—	—	0.59	0.25	—	—
Silicates	0.22	0.56	—	—	0.59	—	—	—

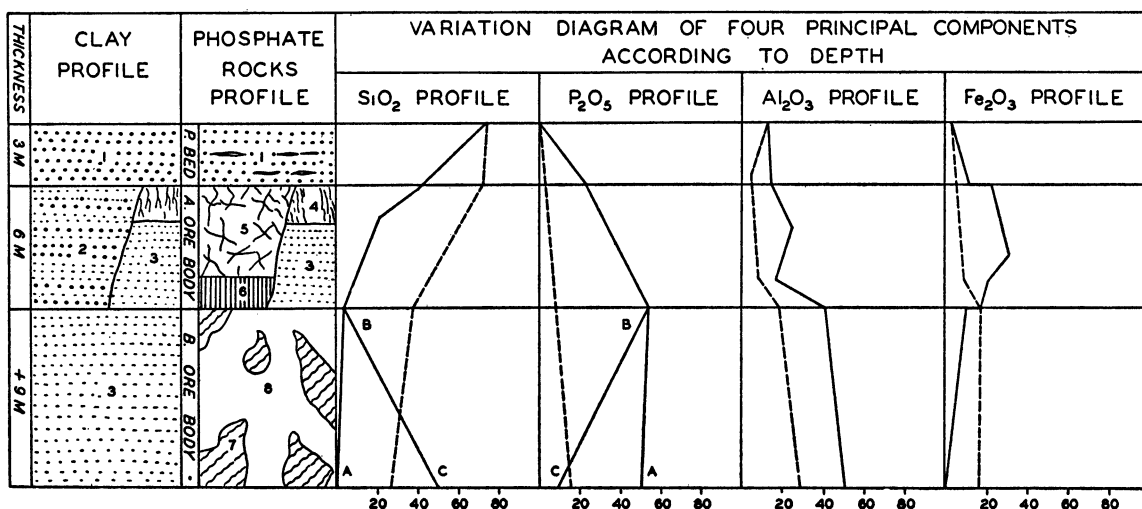


FIG. 66. Variation of chemical constituents in the phosphatized pumice, Kita Daito Jima.

Yamanari gives a generalized diagram (fig. 66) which cannot be completely interpreted but which shows the variation of the main components with depth. In addition to the many analyses given by Yamanari are those from Aso given in table 24, referring to partly dried material.

It will be observed that a considerable amount of material is unaccounted for, even in the more complete analyses. The large quantity of soluble phosphate is curious; this presumably refers to citric-acid solubility.

The total reserve in 1928 on Kita Daito Jima is said (Oinouye) to have been:

TONS	PER CENT OF P_2O_5	TONS OF P_2O_5
40,000 calcium phosphate	30-38%	ca. 12,800
75,000 calcium phosphate	5-15	ca. 7,500
1,650,000 aluminum phosphate	20-45	ca. 528,105
3,350,000 aluminum phosphate	5-20	ca. 417,500
		ca. 965,925

Aso merely indicates that the aluminum phosphate bed had been estimated at 10,000,000 tons. The total P_2O_5 deposited on the island was obviously of the order of 2,000,000 tons.

OKINO DAITO JIMA OR RASA ISLAND

LATITUDE $24^{\circ} 28' N.$, LONGITUDE $131^{\circ} 11' E.$

A small island apparently about 1 kilometer in diameter, of area 990,000 m², and of maximum altitude 32.6 meters, composed of limestone of the same character as the other Daito islands. The phosphate deposit is said by Oinouye to be like that of Kita Daito Jima, save that the calcium phosphate greatly predominates, though in the center of the island there is a patch of aluminum phosphate. This latter material is very low in iron, presumably because the pumice, from which the aluminum was derived, is also poor in iron (Oinouye). It is, however, possible that this material represents phosphatization of a residual clay. Rodgers says that the central part of the island was originally flat or basin shaped and that most of the phosphate occurred in clay between pinnacles. The latter are up to 15 meters high and up to 5 meters wide, standing 6 to 10 meters apart, and now form a typical Karrenfeld, from most of which the phosphate has been removed. The phosphate consisted of a soft massive material with conglomerate and granular ore at the bottom of the deposit. Aso states that 90% of the surface area of the island bore phosphatic deposits, ranging in thickness from 1.4 to 9.1 meters. In places the phosphate is found below sea level. He gives the following analyses:

P_2O_5	$(Al,Fe)_2O_3$
34.76%	2.27%
35.70	6.08
35.24	3.29
35.88	0.72
37.34	tr.
35.19	5.78
36.12	2.63
35.88	4.04
34.19	5.24
36.73	2.80

Fluorine is said to be low, but this statement may refer to material particularly high in sesquioxides. Aso states that by 1928, when commercial operations were temporarily abandoned, 2,100,000 tons of phosphate had been removed. This would presumably correspond to 700,000 tons of P_2O_5 . Oinouye (1928) gives the following reserves, presumably existing at the time of his writing:

TONS	PER CENT OF P_2O_5	TONS OF P_2O_5
2,836,000 calcium phosphate	30-38 %	ca. 964,000
7,732,000 calcium phosphate	5-15	ca. 773,200
302,000 aluminum phosphate	20-45	ca. 98,200
453,000 aluminum phosphate	5-20	ca. 56,700
		ca. 1,894,100

The total P_2O_5 deposited on the island must have been of the order of 2,000,000 tons.

THE RIU KIU ISLANDS

The Riu Kiu arc has had a complex geological history. From the standpoint of the present work the only significant aspect of the earlier part of that history is that it produced a chain of islands composed of a variety of igneous, sedimentary, and metamorphic rocks of Paleozoic and Tertiary ages (Hanzawa, 1935), which during the late Pliocene or early Pleistocene were largely submerged. The seas around the exposed peaks of the islands were evidently warm and supported a rich growth of reef corals, which covered a large part of the area of the islands with a veneer of Riu Kiu limestone, which appears to be not more than 100 meters thick. The upper part of this limestone is mainly reef rock. According to

Hanzawa (1935), the Riu Kiu stage was followed by emergence, the islands standing higher than they do today. He then supposes that a marine transgression without reef formation, the Kunigami stage, occurred. Rodgers (personal communication) indicates that this is illusionary. A period of crustal disturbance followed the Riu Kiu stages. More recently a submergence of about 20 meters, accompanied by reef building, followed, and these post Riu Kiu reefs are now elevated from 2 to 20 meters along the coast. Fringing reefs are still actively growing along the shores of the more southern islands today.

The phosphate deposits to be described mostly occur in clefts in the Riu Kiu limestone. Though there is a little evidence of contemporary phosphatization, more of the deposits are evidently ancient. None are of great extent or now of more than local commercial importance. At least on Miyako Jima they occur some kilometers inland and so are presumably the result of guano deposition at a time anterior to the last small submergence which produced the raised coastal reefs. The exact age of the Riu Kiu limestone underlying the phosphate is unsettled. Hanzawa, who has given the most complete account of the region, thinks it could be either late Pliocene or early Pleistocene, and other Japanese geologists concur in his doubts. Nomura and Zinbô (1935) consider that the molluscan fauna indicates an early Pleistocene date, and the Riu Kiu may be slightly older than the Daito limestone. As is indicated below, one phosphate deposit on Miyako Jima contained an elephant molar apparently at least as old as the Middle Pleistocene. The oldest phosphate deposits, therefore, seem likely to be Early or Middle Pleistocene. On one island, Tarama Jima, phosphate presumably deposited in crevices in the Riu Kiu limestone is said to be covered by raised reef, presumably of the post Riu Kiu 20-meter submergence.

KUSAKAKI SHIMA, INGERSOLL, OR MORRISON ROCKS

LATITUDE 29° 58' N., LONGITUDE 129° 58' E.

A small group of volcanic islets arranged in two clusters, in the northern part of the

Riu Kiu arc. The highest islet is 173.7 meters high, and the total land surface is about 480,000 m². The group is said to have an extensive bird colony. A brown granular phosphate occurs, but the analyses given by Aso indicate that most specimens actually contain little P₂O₅.

N	P ₂ O ₅
0.93%	1.81%
0.62	17.17
1.67	2.19
1.61	2.51
0.68	5.73
0.37	5.95

The fact that it appeared desirable to determine nitrogen suggests that the material was regarded as a product of the modern bird colony. It is, however, evident that little guano existed in most of the samples.

KAMINONE SHIMA

LATITUDE 28° 50' N., LONGITUDE 129° 00' E.

A small volcanic island 287 meters high said to bear 5000 tons of guano (Aso, 1940), but this material was found to contain only 0.5% N and 3.17% P₂O₅, so is mainly not of excretory origin.

KIKAI SHIMA OR KIKAI-GA SHIMA

LATITUDE 28° 20' N., LONGITUDE 130° 00' E.

An island lying to the east of Oshima and composed of Tertiary rocks covered by Riu Kiu limestone and surrounded by raised reef, said by Aso to bear some phosphate. The quantity of good material containing 34% P₂O₅ and 4% (Al,Fe)₂O₃ is small, and the deposits are not worth exploitation.

YORON SHIMA

LATITUDE 27° 03' N., LONGITUDE 128° 25' E.

Said by Yoshiwara (1901b) to be a low, plateau-like island mainly covered by coral rock, presumably Riu Kiu limestone, with some Palaeozoic rocks in the interior. Aso states that two caves on the north coast were supposed to contain phosphate which proved unprofitable. In 1935 other deposits outside the caves were discovered. Aso gives analyses, made in 1932 and presumably, therefore, from the caves:

	P ₂ O ₅	(Al,Fe) ₂ O ₃
Dark brown phosphate	30.05%	4.58%
Soft white	32.11	3.87
Brown	23.64	31.00
Brown	18.23	7.16

OKINAWA

LATITUDE 26° 30' N., LONGITUDE 29° 00' E.

Said by Aso to have scanty deposits in mountain caves, and also 60 cm. to 1 meter below the surface of fields, at a place called Onna-Mura, Yamada.

AGUNI SHIMA

LATITUDE 26° 36' N., LONGITUDE 127° 14' E.

A small island west of Okinawa, said to bear some phosphate (Aso, 1940).

KOBITO, CHIA-U-SU, TIAU-SU, OR KUBA SHIMA

LATITUDE 25° 59' N., LONGITUDE 123° 40' E.

A basalt rock about 3 kilometers long and 180 meters high, one of the Pinnacle group. The islets of this group are said in the "Asiatic pilot" (United States Hydrographic Office, 1930a) to have colonies of boobies, frigate birds, and terns. The islet is probably the Kobi-Shima listed by Aso as bearing some phosphate. No details are given, and the deposit is evidently unimportant.

TORI SHIMA

LATITUDE 26° 36' N., LONGITUDE 126° 51' E.

An isolated volcanic island of recent origin which apparently still emits volcanic gases (Yoshiwara, 1901b). It is about 5 kilometers long and is said by Aso to be barren and in winter to be washed over by waves. It is presumably a bird island, this being the meaning of its name. It was said to bear several thousand tons of guano and from 20,000 to 100,000 tons of phosphatic rock. Aso found no commercially significant deposit; some specimens contained 25%, but most only 17% to 18% P₂O₅. Rodgers was given an analysis referred to Tori phosphate, 1943:

3.6% H ₂ O	21.4% P ₂ O ₅	9.6% (Al,Fe) ₂ O ₃
-----------------------	-------------------------------------	--

MIYAKO JIMA

LATITUDE 24° 50' N., LONGITUDE 125° 20' E.

A large island composed of Riu Kiu limestone overlying Tertiary shales (Hanzawa, 1935), and with some more recent raised reef on the western side. The limestone is elevated to 115 meters (Yoshiwara, 1901a). Aso states that phosphate occurs in fissures in limestone in the higher parts of the island and in caves. The phosphate is said to be either hard or soft. Some contains but 0.5% to 0.8% sesquioxides; other samples contain up to 40% alumina. At one site the molar of an elephant (Tokunaga, 1940) compared to *Elephas trogontherii* and to *Palaeoloxodon namadicus*, was discovered from a phosphate digging about 3 kilometers inland from Harimizu Harbor on the west coast of the island. The tooth was covered with 2 meters of clay and phosphate. It is presumably referable to *Loxodonta (Palaeoloxodon)* sp., and indicates an age not later than the middle Pleistocene. Fragments of bone and antlers of a deer, not unlike *Capreolina mayai*, were also noted by the same author from the Miyako phosphate. In the extreme southeastern part, he examined two narrow slots in the Riu Kiu limestone from which about 50 tons had been taken. He was told that about 2000 or 3000 tons had been dug on the island in 1939, but that the reserves were meager. The following analyses are given by Aso:

White, upper part of bed
Red, dense: 3 m. below surface
Dense
White, light
White, light

Deposited in cave
Deposited in caves
Exposed outcrop

limestone (Hanzawa, 1935). They are said to bear some phosphate, the deposit on the first being the most important. Aso gives no details.

TARAMA JIMA

LATITUDE 24° 92' N., LONGITUDE 124° 42' E.

A small island, most of the surface of which is composed of Riu Kiu limestone, lying to the west of Miyako Jima. Yoshiwara (1901a) and Hanzawa (1935) indicate that the entire island is covered by limestone, but Aso says it was originally two islands and that in the region of the old channel between them there is a deposit of clay without coral rock. Rodgers indicates that this is probably incorrect. The highest point is rather less than 50 meters above sea level, but most of the island has an elevation of less than 14 meters. The phosphate beds are apparently situated in the lower part of the island and are usually covered by up to 1 meter of coral limestone, indicating submergence and emergence since phosphatization. There is apparently some phosphate scattered through the soil of the island, and the water in wells is said to contain up to 3% P_2O_5 . Both hard and soft phosphates are found, as on Miyako Jima. A brown ore containing 10% to 35% P_2O_5 and 2% to 5% $(Al,Fe)_2O_3$ is recorded. In general the quality is low and the quantity present is apparently small. Rodgers was told that 1000 tons were removed in 1939. It is most unfortunate that nothing seems to

H ₂ O	P ₂ O ₅	(Al,Fe) ₂ O ₃
4.87%	26.43%	18.61%
4.27	23.64	11.20
2.87	37.43	2.03
4.18	32.53	6.50
3.78	34.35	3.88
—	32.05	5.28
—	38.00	43.00
3.34	29.21	33.39
14.33	20.27	20.79

The low water content of the penultimate of these meager analyses suggests that the material consisted mainly of calcium, rather than hydrated aluminum, phosphate.

KUREMA SHIMA, ERABU SHIMA, AND
IKEMA SHIMA

Three small, low islands adjacent to Miyako and composed entirely of Riu Kiu

be known about the reef formed over the phosphate deposits.

HADERUMA JIMA OR HATERUMA OR HASYOKAN
ISLAND

LATITUDE 24° 06' N., LONGITUDE 123° 40' E.

A small island of the Sakishima group towards the coast of Taiwan (Formosa).

According to the "Asiatic pilot" (United States Hydrographic Office, 1930a) the island is about 5 kilometers long and 3 kilometers wide, with a maximum altitude of 67.1 meters. The central part of the island forms an elevated plateau bordered by low level land on the east, south, and west. The north side is said by Aso to be steep and apparently represents a Quaternary fault scarp, though his account is obscure. Almost the whole island is covered by Riu Kiu limestone (Yoshiwara, 1901a; Hanzawa, 1935). Aso states that phosphate is distributed irregularly over an area of 6,600,000 m² on the high central plateau and also has been found in fissures, into some of which it has evidently migrated in solution. He gives partial analyses from three localities on the island:

	P ₂ O ₅	(AL,FE) ₂ O ₃
Kihara Yama outcrop	25.0%	5.0%
Kihara Yama from cliff	29.0	4.2
Futoryumochi outcrop	30.0	5.6
Futoryumochi soft below surface	26.5	5.8
Atona Fukahara outcrop	20.0	3.8
Atona Fukahara 10 ft. below surface	18.0	6.0

An analysis given to Rodgers showed:

H ₂ O	P ₂ O ₅	(AL,FE) ₂ O ₃
12.5%	12.5%	9.6%

Aso states that attempts to work the deposit were abandoned, though Noyes (1944) records that 1330 tons of phosphate were exported in 1939, but Rodgers saw Japanese records indicating a production of about 3330 tons in 1939 and 1940.

THE TOTAL QUANTITY OF PHOSPHATE ON THE ISLANDS OF THE WESTERN PACIFIC

The data given above permit the very approximate estimates that are given in table 25.

CHRONOLOGICAL AND CLIMATOLOGICAL REMARKS ON THE PHOSPHATIZED ISLANDS OF THE WESTERN PACIFIC

The islands that have been treated in the present section are of peculiar importance in the theoretical treatment to be developed below. The following classification will be

found useful in such further development.

1. Islands showing feeble contemporary phosphatization, or formation of phosphatic soils:

Marcus Island, perhaps Kusakaki Shima, Kaminone Shima, and Tori Shima in the Riu Kiu Islands, possibly Medinilla in the Marianas, and Grimes Island and Pokaakku or Gaspar Rico in the Marshalls.

The important feature of this class of localities is their unimportance as guano sources, in spite of the fact that bird colonies are known on them. All the islands included in the category, except Marcus Island, probably receive over 2000 mm. of rain per annum. It is quite possible that the phosphatic material exported from Marcus Island represents a more recent phosphatic soil as well as an older and purer phosphatic guano.

2. Unelevated or slightly elevated atolls bearing rich vegetation and apparently without colonies of ground breeding sea birds, but with exposed or lightly covered deposits of phosphatic guano:

The Purdy Islands, the three phosphatized islands of the Ninigo group, Sonsorol, Panna, and Puru, Togobei, probably Gaferut or Grimes Island, Greenwich Atoll, Ngatik, and Ebon.

Except in their smaller reserves, the Purdy Islands, which are well described, evidently represent the condition that would have been observed on Baker or Howland Islands, if, after phosphatization, the rainfall had greatly increased, covering the phosphatic deposits with tropical vegetation. The three phosphatized Ninigo Islands, Sonsorol, Panna, Puru, and Togobei, are evidently comparable to the Purdy Islands. Though Gaferut apparently has a bird colony, it seems to be well vegetated, so that the birds are probably of species that breed in trees. The island is, therefore, more likely to belong in this category than the preceding one. Greenwich Atoll, Ngatik, and Bikar differ in being unelevated atolls bearing phosphate, which on Bikar is apparently covered by waterborne coral debris. None of these deposits can be of any great antiquity. The elevation of those islands that are formed of reef rock, raised 1 or 2 meters, is presumably a post-Pleistocene event, here as elsewhere in the Pacific.

TABLE 25

Locality	Tons	Phosphorus Content	Tons of Phosphorus
Slightly Elevated Islands			
Purdy group	27,000	4.8 %	1,280
Ninigo group	ca. 84,000	10.0 ^a	8,400
Bikar	12,000	10.9	1,310
Ebon	60,000	8.74	5,180
Ngatik	ca. 100,000	8.74 ^a	8,740
Greenwich	100,000	8.74 ^a	8,740
Gaferut	ca. 7,500	6.56	500
Togobei	100,000	12.5	12,500
Sonsorol	47,000	10.8	5,100
Marcus	ca. 7,000	12.0	840
Total (to two significant figures)			53,000
Markedly Elevated Islands			
Fais	700,000	14.9	104,000
Angaur	2,500,000	16.2	405,000
Peleliu	300,000	15.9	48,000
Rota	ca. 300,000	15.7	47,000
Saipan	100,000	8.7	8,700
Tinian	8,600	10.7	900
Aguijan	30,000	8.75	2,600
Kita Daito Jima	ca. 10,000,000	8.60 ^a	860,000
Okino Daito Jima	ca. 10,000,000	8.60 ^a	860,000
Miyako Jima	3,000	13.5	400
Tarama Jima	1,000	9.8	100
Haderuma Jima	3,300	10.8	360
Allowance for other Riu Kiu islands	1,000	10.0	100
Total (to two significant figures)			2,300,000

^a Phosphorus content assumed from comparative and general information.

Tayama specifically mentions the surface of Togobei as an example of his post-Peleliu terrace, which he regards as subsequent to the close of the Pleistocene. Though none of the deposits on these islands was so large as those on the drier Line and Phoenix Islands, that on Togobei must have been very nearly equal to the phosphatic deposit of Howland Island. Aso implies that the Ngatik deposit was of the same order of magnitude as that on Togobei, but as this atoll figures in no other accounts of the region its reserve must be regarded as doubtful.

All the islands in the category under dis-

cussion must receive a great deal of rain, well in excess of 2000 mm. per year. It is very unlikely that they could now become phosphatized. Even if some phosphatic guano derived from tree breeding birds were washed into the lagoons of the raised islands, it is hardly possible that the unelevated islets of Greenwich Atoll, Ngatik, and Bikar could be phosphatized under existing climatic conditions. The number of islands in the present category definitely suggests a period of low rainfall in the equatorial western Pacific during some post-Pleistocene time.

3. Elevated limestone islands or limestone-covered volcanic islands with phosphatic

deposits on Pleistocene or older reef rock:

Fais, Angaur, Peleliu, Eil Malk, Urukthapel, Aguijan, Tinian, Saipan, Rota, Kita Daito Jima, Okino Daito Jima, Miyako Jima, Tarama Jima, Haderuma Jima, and other smaller deposits on islands of the Riu Kiu group.

The most striking feature of this group is the immense size of some of the deposits, notably on Fais, Angaur, Kita Daito Jima, and Okino Daito Jima. On all the islands phosphate lies in depressions in a Karrenfeld, but on Angaur it also occupies wide swampy basins. Unlike Ocean Island and probably Nauru and Makatea, these islands do not appear to have been submerged after the formation of the Karrenfeld but prior to phosphatization. A greater or less amount of terra rossa-like residual soil is found mixed with the phosphatic material.

In spite of a certain uniformity in mode of occurrence, it is unlikely that the deposits on these islands are chronologically homogeneous. The underlying limestone is reasonably ascribed to the lower Pleistocene on the Daito islands, but may be slightly older on the Riu Kiu group. On Miyako in the latter group, the occurrence of *Loxodonta* (*Palaeoloxodon*) sp. in the phosphate deposit suggests a middle or early Pleistocene date. On the

near-by Tarama Jima, similar deposits appear to be covered by post-Pleistocene reef rock. If the Mariana limestone is more or less equivalent to the Riu Kiu limestone, the deposit on Rota, which must have been due to a bird colony inhabiting the emergent summit when most of the island was submerged, is likely to be early or middle Pleistocene if not slightly older. From Tayama's statements about the terraces on Tinian and Aguijan it seems likely that the phosphate on these islands is little younger than that on Rota. The Saipan deposit may have formed later, while, if Tayama is correct in his interpretation, the Fais and Peleliu deposits cannot be later than the late Pleistocene. The position of the Angaur deposit in Tayama's scheme is uncertain.

At least two periods of intense phosphatization appear to be implied by accepting Tayama's account of the raised reefs: one period late in the Pleistocene having produced the Fais, Peleliu, and perhaps the Saipan deposits; the other period, probably early in the Pleistocene, the deposits on Rota and the other Marianas, the Daito islands, and the Riu Kiu Islands. There is nothing, however, to indicate at all certainly that any two or more of the deposits were formed synchronously.

PHOSPHATIC GUANO IN AUSTRALASIA

THE REGION TO BE CONSIDERED in the present section consists of the coasts of Australia and New Zealand, and the islands of the Coral Sea to the east of the former land mass. The whole area is very diversified (fig. 67). The occurrence of guano islands is primarily determined by local conditions, and no general considerations of oceanography, climatology, or ornithology are profitable. The relevant information on these subjects is summarized for each of the areas into which the region has been divided as follows:

Islands in the Coral Sea and off New Caledonia
Islands off New Zealand and other localities on the New Zealand coast and the Subantarctic Islands of New Zealand

Islands in the vicinity of Bass Strait and off Tasmania

Islands off the central part of the south coast of Australia

Islands off the west coast of Australia

Inland avian guano deposits in Australia

The second and third regions are temperate rather than tropical in climate; they are not particularly dry, though by no means excessively wet. Their guano deposits are evidently small and of little commercial importance. They are, however, of some scientific interest, for New Zealand and Tasmania are probably the most temperate regions to exhibit any phosphatization due to bird colonies.

ISLANDS IN THE CORAL SEA AND OFF NEW CALEDONIA

A number of islands in the Coral Sea have yielded guano. Off the Australian coast, Raine Island outside the northern part of the Great Barrier Reef and a group of islands forming a southern extension of the Reef are guano islands. There are a large number of low "sand cays" within the Reef, usually covered with low shrubs which have led to the formation of dunes. Though some of these islands support large bird colonies (Steers, 1930), only one island in this region, namely, Holborne Island, which is not a sand cay, ever seems to have produced much phosphate. The peculiar distribution of the northeast Australian guano islands is undoubtedly climatically determined.

In the central part of the Coral Sea the Chesterfield Islands were sources of guano, while off the northern end of New Caledonia there is a group of guano-producing islands. Finally Walpole Island, an elevated coral island east of the southern tip of New Caledonia and so not within the Coral Sea, may be conveniently discussed with the other islands of this region.

OCEANOGRAPHY

The detailed movements are best understood along the Great Barrier Reef. Immediately outside the Reef the current in general sets south, and according to Orr (1933) is obvious in calm weather as a slight

southerly drift. Locally, however, a northern set may be observed, suggesting the existence of eddies. Orr says that farther out, about 30 to 40 kilometers from the Reef, the surface movement is largely dependent on the winds; a current at about 1 knot sets with the wind when the southeast trade wind is blowing. There is some evidence of upwelling of water from a depth of below 100 meters along the outer edge of the reef (Orr, 1933), and Orr suspects that vertical mixing will also occur against such small islands as are surrounded by deep water, farther out to sea.

CLIMATOLOGY

The whole region is one of markedly seasonal rainfall, the wet season culminating in January or February. The dry season, which here as elsewhere on the eastern continental coasts of the Southern Hemisphere is the season of the southeast trade winds, culminates in August. Along the Australian coast orographic factors modify the quantity of rain falling, though not its seasonal distribution. The highest mean annual precipitation known in Australia is recorded from the eastern slope of the Bellenden-Ker Mountains which rise just inland from the coast around latitude 17° 15' S. In this region stations exist with up to 4200 mm. mean annual rainfall. North and south the amount falls off rapidly, though isolated areas may

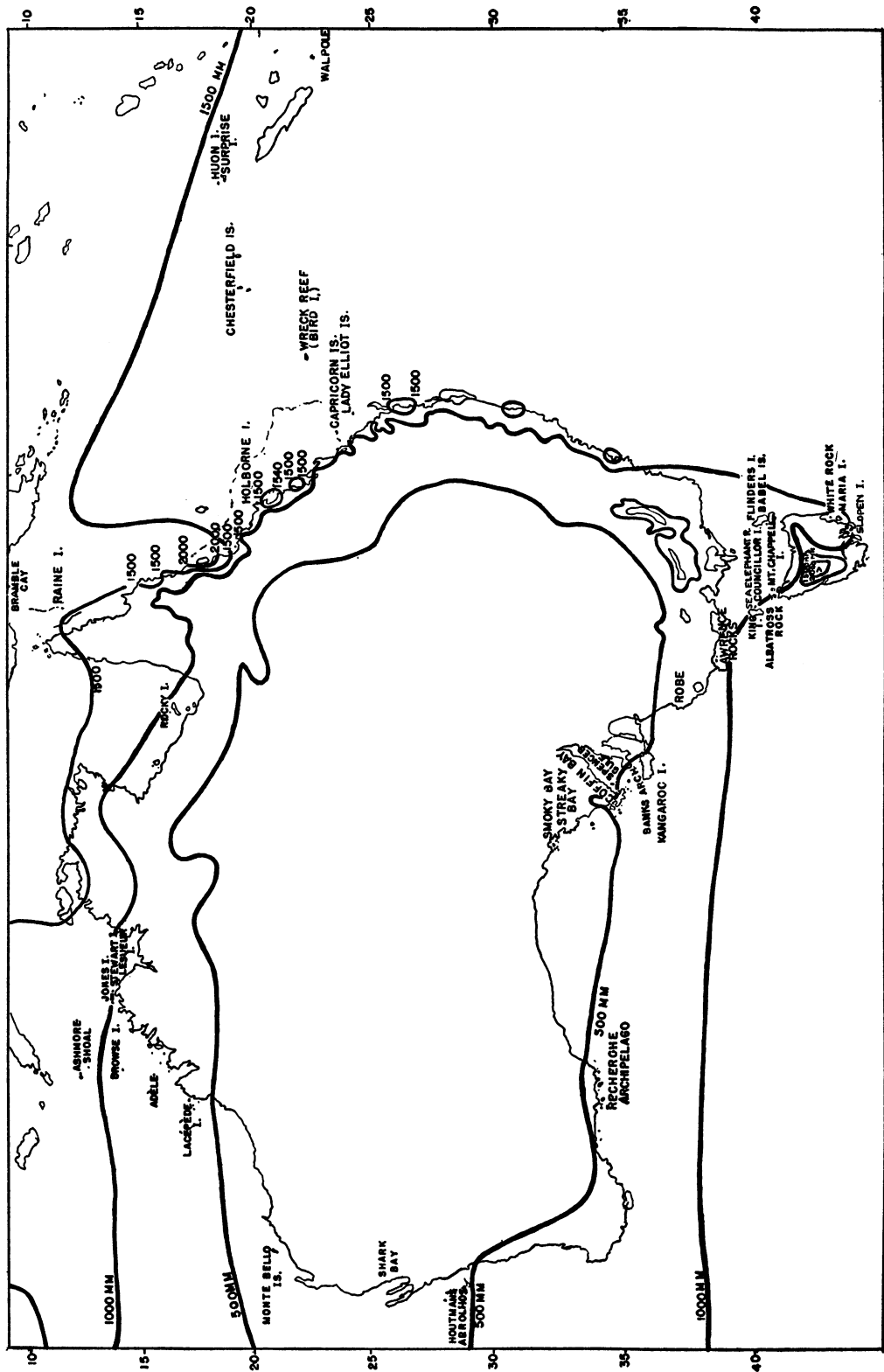


Fig. 67. Map of Australasia with isohyets.

have up to about 2000 mm. Evidence from the short available record at Willis Island indicates that outside the Barrier Reef the rainfall, at the latitude of greatest precipitation on the coast, declines rapidly. For the islets of the open Coral Sea a mean annual precipitation of not much over 1000 mm. per annum may be expected. The southern part of the Gulf of Carpentaria appears to have a similar rainfall regime.

ORNITHOLOGY

The general distribution of birds on the northeast coast of Australia is well known, but detailed descriptions of the avifauna exist for few of the individual localities to be discussed. The information collected by North (1912, 1914) indicates that boobies are likely to be important only in the northern part of the area, though Fairfax Island, a phosphatized island in the Bunker group, has a colony of *Sula leucogaster plotus* (Ellis, 1937). Breeding colonies of all three tropicopolitan boobies exist on Raine Island and on other islands in the Torres Strait region. North indicates that throughout the Barrier Reef region *Sterna fuscata serrata* Wagler, *Thalasseum bengalensis torresii* Gould, *T. bergii gwendolenae* (Mathews), and *Anous stolidus pileatus* (Scopoli) are the commonest terns forming large colonies. The mutton bird, *Puffinus t. tenuirostris* (Temminck), forms a large colony on North-West Island in the Capricorn group (Ellis, 1937). The Australian pelican, *Pelecanus conspicillatus* Temminck, is said by Ellis to have been the chief sea bird breeding on Rocky Island.

DESCRIPTION OF THE ISLANDS

ROCKY ISLAND

LATITUDE 16° 11' S., LONGITUDE 139° 29' E.

In the southern part of the Gulf of Carpentaria, said by Ellis (1937) to be about 1.6 kilometers long and 600 meters wide. The maximum altitude is about 12.2 meters above sea level. The island is apparently formed of consolidated coral sand and debris, phosphatized in places to a depth of about 5 cm. The phosphate was worked in the early 1890's and was regarded as a rich commercial deposit, though it contained appreciable amounts of alumina and ferric oxide. The

material was hard to obtain and to load; a ship might take three days making fast to the buoy. The phosphate was loaded in 60-pound sacks. It seems improbable that more than a few thousand tons were present. Ellis notes that the only breeding sea birds were pelicans, though shags and cranes were also observed. Ellis states that the other small islands of the Gulf of Carpentaria have been prospected, but that no phosphate has been discovered on them.

BRAMBLE CAY

LATITUDE 9° 08' S., LONGITUDE 143° 52' E.

A sandy island in the Great Northeast Channel approach to Torres Strait. It is 3 meters high and has a depressed central region containing a little grass and other low growing plants. Sea birds are numerous. North (1912) mentions *S. leucogaster plotus*, observed by Sir William Macleay, breeding on the island, the nests, consisting of a few dried sticks and twigs, placed so closely together that it was difficult to walk without treading upon them. Gould (1865) notes that Macgillivray found prodigious numbers of *Sterna fuscata serrata* and *Anous stolidus pileatus* breeding in May and June on this, as on the next island. According to Crowther (1939), Dr. W. L. Crowther leased the guano rights, apparently in 1865. Heiden (1887) records that 410 tons of phosphatic guano reached Hamburg from Bramble Cay in 1878. Ellis does not mention Bramble Cay as one of the localities worked by J. T. Arundel and Company.

RAINE ISLAND

LATITUDE 11° 35' S., LONGITUDE 144° 05' E.

An island lying between the Barrier Reef and Great Detached Reef. It is about 600 meters long and 450 meters wide and reaches an altitude of 3 meters. According to the "Australia pilot" (United States Hydrographic Office, 1930c) the center of the island is slightly depressed and formerly contained a layer of guano 6 to 8 feet thick, divided at about 2 feet from the surface by a layer, 3 inches thick, of oolitic coral sand rock.

Raine Island is the site of an important bird colony, described by W. Macgillivray (*in* North, 1912) who says that the island was

covered from end to end with nests and birds, and of these birds nine-tenths were *Sula leucogaster plotus* sitting on eggs with young in various stages. The nest is described as a mere depression, but around it lay coral, sticks, and other objects brought by the bird during incubation. *S. dactylatra* is apparently the next most abundant species on Raine Island, but the island also has a sufficient number of bushes to support a breeding population of *S. sula rubripes*. It is clear from Macgillivray's account that the breeding season of all three species was drawing to a close at the end of October, 1910. *S. s. rubripes*, of which some young birds were already flying, presumably starts breeding a little before the other two species.

A small colony of *Fregata*, with about 50 young, fully feathered but as yet unable to fly, was observed on the eastern side of the island. The nesting season is believed to begin early in the winter, at the same time as that of *Sula sula rubripes*, but it seems probable from the account that egg laying is better synchronized than in the case of the boobies, in which all stages from eggs to young birds ready or almost ready to fly were observed at the same time. As well as frigate birds, which live cleptobiotically on the fish caught by boobies, the latter birds have on Raine Island to contend with depredations of the gull *Larus novae-hollandiae* which steals their eggs.

Terns appear to be plentiful. Gould (1865) says that *Sterna fuscata* frequents the island in prodigious numbers. W. Macgillivray (*in* North, 1913-1914) indicates that he observed the species and also *Anous stolidus* in great numbers, but no mention is made of nidification of the former, and the latter are expressly stated not to have begun breeding at the end of October. Other records from the Barrier Reef region given by North strongly suggest that these terns, as well as *S. bengalensis torresii* and *S. bergii*, breed later than the boobies and that the later stages of rearing the young probably are prolonged into the rainy season. It is not impossible that the incidence of guano on this coast is in part determined by the presence of the earlier breeding Sulidae whose droppings will be dried out and to some extent consolidated before the rain begins. Farther south boobies

appear to be less common, though *S. leucogaster plotus* occurs on Fairfax Island and *S. dactylatra* on Norfolk and Lord Howe Islands.

Ellis says that the phosphate of Raine Island was loaded into sailing ships of 1000 to 1500 tons, all bound for Europe save two that took their cargoes to Melbourne. It is clear that a considerable quantity, doubtless of the order of tens of thousands of tons, was present.

HOLBORNE OR HOLBOURNE ISLAND

LATITUDE 19° 44' S., LONGITUDE 148° 22' E.

This seems to be the only source of phosphatic guano within the central part of the Barrier Reef. It is described by the "Australia pilot" (United States Hydrographic Office, 1930c) as being about 1.2 kilometers long and having a maximum altitude of 109.7 meters with a cliffy north coast and with the south side covered with grass and bushes. Dunstan (1928) states that an estimated 400,000 tons of phosphatized coral rock are present on the island, having a composition:

H ₂ O	3.00%	
Organic matter	14.04	
N		0.19
K ₂ O (sol.)	0.45	
CaO	33.00	
(Al,Fe) ₂ O ₃	6.4	
CO ₂	8.00	
P ₂ O ₅	16.11	
SiO ₂ , etc.	18.30	

It is possible that this does not represent contemporary phosphatization.

LADY ELLIOT ISLET

LATITUDE 24° 08' S., LONGITUDE 152° 46' E.

A small coral islet surrounded by a reef of mean diameter about 290 meters and reaching an elevation of 4.6 meters. It is said to be covered with scrub and stunted trees about 10 meters high (United States Hydrographic Office, 1930c). The islet is listed by Power (1925) as one of the islands now no longer worth working. Lady Elliot Island was apparently one of the chief localities yielding guano to Dr. W. L. Crowther in the 1860's (Crowther, 1939). The total output from the island and from Wreck Reef is given as:

	Tons
1863	462
1864	854
1865	1600 (estimated)

In spite of Crowther's activities, Lady Elliot Island was again worked by J. T. Arundel and Company in 1893, several hundred tons of guano being loaded into each ship coming to the island (Ellis, 1937). The total amount of phosphatic material originally present must have been of the order of thousands of tons.

THE BUNKER ISLETS

Three small islets of the same character as Lady Elliot Islet. The largest, Lady Musgrave Islet, is about 600 meters long and covered with trees and scrub. Two smaller but otherwise similar islets, Fairfax and Hoskyn Islets, lie to the north-northwest. Bunker is mentioned by Power as a guano island now not worth exploitation. Ellis (1937) says that the islands were worked before 1898, but that the venture was hardly a profitable one, Lady Musgrave Island having but a meager deposit and Fairfax Island having its phosphate much mixed with coral and shingle.

THE CAPRICORN ISLETS

A group of scattered islets, similar to the preceding, between latitude 23° 30' S., longitude 153° 08' E. (One Tree Islet), and latitude 23° 33' S., longitude 151° 44' E. (Masthead Islet). Meise (1938) quotes Nevermann (*in litt.*) that the group produced guano, but regards the report as doubtful. The existence of guano islands in the group is, however, confirmed by Ellis (1937) who says that islets in the group were worked in 1898. The deposit was of medium quality on North-West Island but the venture did not prove very profitable.

BIRD ISLET, WRECK REEF

LATITUDE 22° 11' S., LONGITUDE 155° 20' E.

Lies farther out from the coast than the preceding localities. It consists of a small oval islet of mean diameter 290 meters and, with its vegetation, but 5.5 meters high. Other sand cays exist on Wreck Reef, but Bird Islet alone has vegetation. The "Australia pilot" states that the "surface is flat and bare in the

center, surrounded by tufts of rank, wiry grass and creeping plants, which thrive by means of the guano deposited by the vast number of birds which resort to the islet." Crowther (1939) states that Dr. W. L. Crowther worked the island in the 1860's when it was, with Lady Elliot Islet, clearly the most productive of the eastern Australian guano islands.

An analysis published by Voelcker (1876) of phosphatic guano from Bird's Island, described as a small coral island in the south Pacific, presumably refers to the islet on Wreck Reef. Voelcker found:

H ₂ O	6.92%
Organic matter	4.8
Ca ₃ P ₂ O ₈	80.44
CaCO ₃ , MgO, etc.	6.38
Alkalis	1.34
SiO ₂	0.12

A supposed island named Pilgrim Island which Crowther (1939) states was believed to be in the Coral Sea, was leased as a guano island to Dr. W. L. Crowther, but the lease was revoked in 1869 as the island could not be found. The position given, latitude 24° S., longitude 104° W. (*sic*), is obviously erroneous.

THE CHESTERFIELD ISLANDS

A group of three reefs bearing 13 islets, the largest of which, Long Island (latitude 19° 53' S., longitude 158° 19' E.), is about 1.6 kilometers long and 6.1 meters high. The island is said by Chevron (1880) to have trees, but by the "Australian pilot" (United States Hydrographic Office, 1930c) now to be covered with grass, with two coconut trees, and to bear ruins of huts. The Chesterfield Islands are known to have been worked for guano in the nineteenth century. Meise states that the group was annexed by France in 1878 on account of the guano. De Sornay (1922) states that phosphatic guano was exported from the group to Mauritius between 1880 and 1883. Chevron (1880) reported that on Long Island there were 185,000 cubic meters of phosphatic material, and but a few tons on the other islands. The deposit appears to have contained the equivalent of 40% to 62% Ca₃P₂O₈.

Crowther (1939) records that Brampton Shoals and islets, given as lying in latitudes

18° 49' to 19° 35' S., longitudes 158° 02' to 185° (*sic*) 40' E., were leased as guano islands to Dr. W. L. Crowther in 1862. This statement can refer only to Bampton Island (latitude 19° 08' S., longitude 158° 40' E.) and some associated cays and islets, just to the south of the Chesterfield group. Power does not mention either Chesterfield Islands or Bampton Island.

THE D'ENTRECASTEAUX REEFS

Encircle two large, lagoon-like areas to the northwest of New Caledonia. On the western side of the oval reef surrounding the southern or Surprise Island lagoon there are three islands, Surprise, Fabre, and Le Leizour; on the reef surrounding North Lagoon there is a single island, Huon. The whole group of islands is sometimes called the Huon group, but all the material described as Huon guano actually came from the three islands on the southern reef.

SURPRISE ISLAND

LATITUDE 18° 28' S., LONGITUDE 163° 08' E.

A nearly circular island of mean diameter about 0.5 kilometers. The altitude of the island is about 2 meters above the reef on which it stands. The shore is formed by a gently sloping white sandy beach. There appear formerly to have been trees on the island, as the "Pacific islands pilot" (United States Hydrographic Office, 1928b) says that working of the guano deposits has completely changed the aspect of the island; "a few coconut palms are the only trees now to be seen." In this respect Surprise Island appears to differ from the other islands which still have arboreal vegetation, suggesting that though the deposit on Surprise was smaller than that on Fabre and Le Leizour Islands, it may have been more valuable, and so more completely exploited.

It appears from Power's (1925) account that the guano of Surprise Island resembled that of other unelevated Pacific islands and consisted of coffee-colored loose or "alluvial" guano lying over partly phosphatized coral sand and shell grit cemented together by phosphate. The deposit is said to have been purer in the center of the island than peripherally where it was contaminated with wind-blown sand. Elschner (1913), however,

indicates that the phosphate consisted of large blocks of phosphatized coral sandstone embedded in loose sand; he says that the blocks could be detected by probing. According to Chevron (1880) the original reserve consisted of 88,200 cubic meters of phosphatic material. Some of the analyses given below for Huon phosphatic guano probably refer to Surprise Island, which seems to have been the most important source of the D'Entrecasteaux Reefs. Power, though he gives no full analysis, indicates that Surprise Island guano had a sesquioxide content of 0.68% Fe_2O_3 and 0.22% Al_2O_3 .

FABRE ISLAND

LATITUDE 18° 16' S., LONGITUDE 163° 02' E.

Described as being about twice as long as Surprise Island and of about the same width; it appears to be somewhat more elevated; the "Pacific islands pilot" (United States Hydrographic Office, 1920a, 1928b) gives 3 meters as the maximum elevation above the reef. It is said in the same works still to be covered with moderately high trees. Chevron gives the original reserve as 107,019 cubic meters of phosphatic material. Both the "Pilot" and Power say that guano occurs, and from the latter's account it appears to have been worked, though the deposit evidently appeared less satisfactory than that of Surprise Island.

LE LEIZOUR ISLAND

Separated from Fabre Island by a deep channel, is about 1.2 kilometers long and about half that width. It is said to be similar in structure to the other islands, and about 3.7 meters high. It has trees 6 meters high. Chevron gives the original reserve as 132,462 cubic meters. Power says that guano was worked on it, and the "Pacific islands pilot" states that a mole was built for the loading of guano vessels. This suggests a good deposit.

HUON ISLAND

LATITUDE 18° 03' S., LONGITUDE 162° 58' E.

On the northern reef is an elongate island about 800 meters long with sand spits at each end and with trees in the middle part, to the north of which there is coral conglomerate ("Pacific islands pilot," United States Hydro-

graphic Office, 1920a, 1928b). Unlike the three islands on the southern reef, Huon had negligible deposits, probably owing to occasional flooding by the sea (Chevron, 1880).

Dixon discusses guano from the "Huon Islands" and indicates categorically that his material came from two islands, one of which must obviously have been, and both of which presumably were, on the southern reef. The material is said to have contained 20% to 25% organic matter, mostly apparently of vegetable origin though somewhat nitrogenous. From 2% to 10% CaCO_3 is said to have been present, though the guano was stated to have been acid, presumably giving acid aqueous extracts. Dixon concluded that the organic matter protected the calcium carbonate from attack by acid phosphate and that if the latter were leached out, descending to a lower layer poor in organic matter, this layer would be enriched in phosphate, just as he had found on Malden Island. Some calcium carbonate is said to be formed on ignition, supposedly from an organic calcium salt.

CO_2 in ash as per cent of unignited guano	4.57	1.54	1.50
CO_2 per cent in unignited guano	4.17	1.27	1.12
Excess CO_2 fixed in ash as per cent of unignited guano	0.40	0.27	0.38

The phosphate and calcium carbonate contents were as follows, samples 1 to 3 referring to one island, 4 and 5 to another:

	P_2O_5 TOTAL	P_2O_5 Sol.	CaCO_3
1	29.96%	0.18%	9.47%
2	31.68	0.53	2.88
3	31.57	0.44	2.54
4	32.14	0.42	2.47
5	34.63	0.63	2.29

Chevron (1880) also describes the Huon guano beds without specifically indicating from which of the islands on the southern reef his material came. He states that the deposits varied from a few centimeters in thickness up to 60 to 70 cm., the mean depth being 50 to 55 cm. The material contained fragmentary bird bones and the debris of egg shells. On analysis Chevron found:

H_2O	9.74%	
Organic	19.90	
N		1.16
Fe_2O_3	0.24	
CaO	37.60	
MgO	0.09	
K_2O	0.28	
Na_2O	0.18	
P_2O_5	28.59	
SO_3	0.44	
SiO_2	0.08	
CO_2	3.01	
Cl	0.11	
F	tr.	

A statement by Aikman (1894) that Huon guano contains 28% P_2O_5 doubtless is based on this analysis.

Heiden (1887) reports that 163 tons of phosphatic guano reached Hamburg from the Huon Islands in 1879, and 648 in 1880, but by 1881 only 50 tons were received.

WALPOLE ISLAND

LATITUDE $22^\circ 38'$ S., LONGITUDE $168^\circ 56'$ E.

An elevated coral island somewhat over 3 kilometers long and 1.6 kilometers wide. The island is said to present the appearance of a narrow table, rising to a height of 70 meters at the north end ("Pacific islands pilot," United States Hydrographic Office, 1928b). Power (1925) says that the precipitous cliffs bear traces of at least five marine terraces. A narrow shore reef fringes the island. The vegetation is said to be stunted, and the island frequented by many sea birds, the "Pacific islands pilot" indicating the "black gannet" by which *Sula leucogaster plotus* is presumably implied. The guano deposit is said by Power to be on the top of the island and to lie between pinnacles up to 10 meters high ("a few inches to 20 or 30 feet"). The published chemical data are inadequate, but Power says that 6.72% Fe_2O_3 and 12.57% Al_2O_3 occur, although the island shows no indication of volcanic activity and apparently consists exclusively of coral rock. Power considers that the Krakatoa eruption of 1883 cannot be the source of the sesquioxides, as, if it had been, other deposits, such as that on Surprise Island, would have contained much alumina and ferric oxide. It is probable that on Walpole Island, as elsewhere, the sesquioxides are derived from a residual soil formed by decomposition of reef rock.

ISLANDS OFF NEW ZEALAND AND OTHER LOCALITIES ON THE
NEW ZEALAND COAST AND THE SUBANTARCTIC ISLANDS
OF NEW ZEALAND

The localities discussed below in which contemporary guano deposition is occurring are unimportant commercially. Certain of them, namely, The Snares, Bounty Island, and Antipodes Island, are of some interest in that they lie in the productive region just north of the Antarctic convergence and have immense bird colonies. They indicate what happens when vast masses of guano are deposited on islands climatically unsuitable for its retention.

Apart from these marginal cases, there is a deposit of phosphate at New Plymouth, which is apparently due to an ancient bird colony. This deposit presents peculiar and remarkable features.

CLIMATOLOGY

New Zealand lies just north of the zone of persistent westerly winds, and though the wind direction usually has a westerly component, the western direction and the force of the wind are less constant and less great than in the Subantarctic Ocean immediately to the south.

South Island, with its longitudinal mountainous axis and more persistent westerly wind direction, forms a gigantic rain shadow. The western coast of the island receives over 1800 mm., and south of latitude 42° S. over 2500 mm., of rain per annum. Almost the whole east coast of South Island and that part of the east coast of North Island south of Napier receive less than 1000 mm. per year. The northern and northeastern coast of North Island occupy an intermediate position between the two extremes.

The Subantarctic Islands south of New Zealand are evidently windier (McDonald, 1938) than the main islands and appear to have mean annual precipitations in excess of 1000 mm. per annum. Campbell Island is given by Schott as having 1460 mm. per annum; Macquane, 1225 mm. per annum. Chatham Island to the west of South Island has a drier climate, with a mean annual precipitation of about 900 mm. per annum (Kidson, 1930). None of these islands have guano deposits or exhibit biogenic phos-

phatization. The Snares just south of the wet southern tip of New Zealand are probably wetter than the islands on which stations exist. Antipodes and Bounty Islands probably have more rainfall than Chatham Island to their northeast and possibly less than Campbell Island to their southwest, though Speight and Finlayson speak of persistent rain on Bounty Island. It must not be forgotten that on all these islands temperatures are fairly low and evaporation is consequently reduced. Thick peat deposits are developed on some of them, and they are totally unlike the islands having comparable rainfall in the tropical Pacific.

OCEANOGRAPHY

The surface movements of the ocean around New Zealand are mainly determined by the predominant wind and form a part of the general system of currents moving to the east. The detailed movements of water are complex and in large measure of little significance in the present study. The most important oceanographic aspect of the region is the fact that the Subantarctic Islands lie little north of the region of the Antarctic convergence and that this part of the ocean is extraordinarily productive. In consequence immense birds colonies exist here as on other subantarctic islands in other oceans.

It is evident from Townsend's maps that a population of the southern right whale, *Balaena australis*, concentrated off the east coast of South Island of New Zealand in the late southern summer. Such populations were somewhat discontinuously distributed along latitude 40° S. on the southern parts of all the oceans, and the discontinuities may indicate regions of high fertility.

DESCRIPTION OF THE LOCALITIES

THE SUGAR LOAVES, NEW PLYMOUTH,
TARANAKI

LATITUDE 39° 04' S., LONGITUDE 173° 59' E.

A pair of conical islets, 57.9 meters and 81.1 meters high, off New Plymouth (fig. 68). They are composed of trachyte which is



FIG. 68. Taranaki, with the Sugar Loaves. After British Admiralty.

fissured. In the fissures is a yellowish white or pale cream, compact, soft, cryptocrystalline material, described by Hector and Skey (1865) and by Cox (1883) as taranakite. Thin seams of a dark yellowish brown material in the taranakite were identified as wavellite by Hector and Skey. Recent study has shown that the materials from other perennially damp localities, mainly caves, in other parts of the world, described as minervite and palmerite, are identical with taranakite. The material referred to wavellite proves to be vashegyite (Bannister and Hutchinson, 1947) The original analysis of taranakite gave:

P ₂ O ₅	35.05%
Al ₂ O ₃	21.43
Fe ₂ O ₃	4.45
FeO	tr.
CaO	0.55
K ₂ O	4.20
Na ₂ O	tr.
Cl	0.46
SO ₃	tr.
H ₂ O	33.06
Insol.	0.80

It is reasonably certain that the Sugar Loaves were once bird islands and that the phosphate of the minerals was derived from guano as Hector and Skey supposed. No other biogeochemical phosphatization is known on the wet western coast of New Zealand.

WHITE ISLAND OR WHAKARI,
BAY OF PLENTY

LATITUDE 37° 31' S., LONGITUDE 177° 11' E.

An island bearing an active volcano 328 meters high, situated in the middle of the Bay of Plenty. According to the "New Zealand pilot" (United States Hydrographic

Office, 1929b) it has a gannet (*Morus serrator rex*) colony, and Morgan states that guano occurs.

The locality has been described by Walsh (1930a, 1930b) who indicates that the main gannetry is on the northwest point of the island. The soil is said to be soft, mainly composed of guano and honeycombed with the burrows of mutton birds. The upper parts of the island are covered with pohutukawa trees, said to be growing on leached guano 12 meters (40 feet) thick. Walsh gives a good photograph of the gannet colony, though some of his natural history is at least of doubtful authenticity. He says that the guano has been used as a fertilizer by the Maoris for years, but it is not clear if this remark implies utilization prior to the arrival of Europeans familiar with the use of guano elsewhere.

CAPE KIDNAPPERS OR MATAU-A-MAUI

LATITUDE 39° 38' S., LONGITUDE 177° 06' E.

At the southern end of Hawke Bay, close to the port of Napier, described in the "New Zealand pilot" (United States Hydrographic Office, 1929b) as "a high point with white cliff (argillaceous clay) on either side of it, and two remarkable rocks off it." The cape is, as has been indicated, the site of a gannet colony, and Morgan states that it produces guano. The colony has been recently described by Wodzicki and McMeekan (1947), who found that the main breeding ground, on a saddle on the cape, supported 2265 nests. Two subsidiary overflow colonies have developed in recent years. While the colony may not have existed in Captain Cook's time, it was certainly flourishing 50 years ago,

but in that period only a few inches of guano have accumulated. It is evident that most of the guano produced must be lost.

WHITE ISLET

LATITUDE 45° 58' S., LONGITUDE 170° 35' E.

A guano-capped islet southwest of Cape Saunders near Dunedin and about 1 mile from the coast. It is said to have phosphatized volcanic rock similar to that found at the next locality.

GREEN ISLET

LATITUDE 45° 58' S., LONGITUDE 170° 31' E.

About 4 miles west of White Islet, said by Morgan to have a guano deposit, lying on volcanic rock, which through weathering and the action of phosphate solution has been converted into a mixture of hydrous phosphates of lime, alumina, and iron, containing 19% to 20% P_2O_5 . This deposit was apparently worked in the 1890's. Other guano islets may have existed on the east coast of South Island (Morgan, 1915).

THE SNARES

LATITUDE 48° 01' S., LONGITUDE 166° 35' E.

A group of granite islands covered in most places with a layer of peat 2.5 meters thick. They have precipitous cliffs. The interior is mainly covered with *Olearia* scrub, but there are also meadows of tussock grasses (Cockayne, 1909). The largest island, East Island, is about 2.4 kilometers long. Four western islets lie about three kilometers away and are not over 400 meters long. The islands are frequented by pinnipeds, mainly *Phocarctos hookeri* (Gray), with fewer numbers of *Arctocephalus forsteri* Lesson. They have large bird colonies. Penguins are very abundant, the chief species being *Eudyptes pachyrhynchys* G. R. Gray, though *E. cretatus filholi* also breeds on the group. *Daption capensis* (Linnaeus)¹ is said to nest in myriads on the western islands of the group. *Diomedea bulleri* Rothschild and *Macronectes gigantea* (Gmelin) nest on the islands. The mutton bird, here

¹ Snares is not listed by Peters (1931) as a breeding station, but Waite and the "New Zealand pilot" mention the vast numbers reported on the islands of the group.

presumably *Puffinus griseus*, evidently has a considerable colony on The Snares (Waite, 1909).

Cockayne says that the streams of the island are liquid manure, due to bird droppings. He describes the effects of penguin colonies on the vegetation. Recently established rookeries have tussock grass merely flattened down by the birds. In old rookeries the ground becomes bare of plants and consists of a mass of mud with guano, feathers, decomposing dead birds, and eggs. The rookery is finally abandoned in such condition and slowly is occupied by *Tillaea moschata* De Candolle, normally a halophyte, which grows in great luxuriance. A few plants of the coastal rock plant *Colobanthus muscoides* Hooker may also occur. As the excessive fertilizing effect of the bird droppings wears off, the tussock grass *Poa foliosa* re-establishes itself, and the locality becomes a meadow again. Though no deposits of avian guano apparently occur, Aston (1909) gives an analysis of sea lion dung from the island, as follows:

H ₂ O	10.20%
Free NH ₃	0.08
Total N	1.75
Organic matter	25.94
P ₂ O ₅	32.18
CaO	27.20
MgO	1.03
Na ₂ O	1.63

Compared to sea lion feces analysed from Peru (p. 72) the phosphate is extremely high. It is possible that the animal producing the Snares Island dung had been feeding on invertebrates rather than fish.

THE BOUNTY ISLANDS

LATITUDE 47° 41' S., LONGITUDE 179° 03' E.

A bare and rugged group, about 5 kilometers long, of nine granitic islands with outlying rocks. The highest island has an altitude of 88.4 meters (Speight and Finlayson, 1909). There is no true terrestrial vegetation, but a fresh-water alga is said to occur on exposed rock surfaces. The climate is evidently very humid, and though it seems unlikely that more than 1000 mm. of rain falls per year Speight and Finlayson speak of the rain as almost constant. The Bounty Islands are

the site of important bird colonies. The most numerous species are the penguins *Eudyptes crestatus filholi* and *E. sclateri*. Aston estimates that there are 10 penguins per square yard on the level parts of the islets and that the whole population consists of millions of birds. The albatross *Diomedea cauta salvinii* (Rothschild) has a colony on the islands, as does *Sterna vittata bethunei* Buller. The continual trampling of the feet of birds is believed by Speight and Finlayson to be responsible for the smooth surface of the rock of the islands. Immense amounts of guano are said to be deposited annually only to be washed away, though a little collects between boulders. Aston states that the polished surface of the granite has a coating that looks like calcium carbonate but on analysis proves to be phosphatic. He gives the following analysis of guano from crevices in the rock, which he implies will ultimately be washed away:

H ₂ O	73.01%
Organic matter total	14.47
Organic matter soluble in water	2.30
Organic matter insoluble in water	12.17
N in organic matter insoluble in water	1.02
NH ₃ free	1.23
NH ₃ water soluble	0.20
P ₂ O ₅ total	5.84
P ₂ O ₅ water soluble	1.12
(Al,Fe) ₂ O ₃ water insoluble	0.24
CaO water insoluble	1.86
MgO water insoluble	0.60
Na ₂ O water insoluble	0.23
NaCl water soluble	1.02
K ₂ O water soluble	0.21
SiO ₂ water insoluble	0.12
S water insoluble	0.24

The dry material contains:

P ₂ O ₅	22.80% (=9.95% P)
N	8.92

This material seems to be quite different from Peruvian guano. The low calcium content relative to phosphorus may be due to the birds' having fed primarily on invertebrate food, such as cephalopods. The sea lion dung from The Snares shares this peculiarity, though in a less extreme manner. The low nitrogen content of the insoluble organic matter is curious. The total nitrogen is considerably lower than would be expected from Peruvian experience, and it seems possible that under humid conditions there is a tend-

ency for the nitrogenous excreta of birds to form humic material low in nitrogen.

Aston also gives the following analyses of the polished phosphatized crust (I) and the interior of the rock (II) on which it occurred:

	I	II
Ignition loss	5.00%	1.15%
SiO ₂	48.25	66.95
Al ₂ O ₃	13.30	12.50
Fe ₂ O ₃	4.14	4.60
TiO ₂	0.35	0.60
P ₂ O ₅	11.77	1.90
CaO	9.70	3.25
MgO	0.83	0.43
Na ₂ O	4.42	4.60
K ₂ O	2.76	4.18

The iron and alumina must come from the granite; if it be assumed that they are more or less quantitatively retained, there has clearly been a loss of silica, of potassium, and of titanium. The last-named loss is probably not significant. A great gain of calcium and an even greater gain of phosphorus have taken place. These elements must have come from guano. It is reasonably certain that a part of the phosphorus is present as some aluminum phosphate mineral.

ANTIPODES ISLAND

LATITUDE 49° 40' S., LONGITUDE 178° 50' E.

A volcanic island of precipitous appearance, with several small outlying islets. The slopes above the cliffs are covered with tussock grasses, notably *Poa litorosa* Cheeseman, and *Coprosoma* scrub is found in sheltered places (Cockayne, 1909). The island has considerable colonies of the penguins *Eudyptes crestatus filholi* Hutton and *E. sclateri* Buller. Large numbers of wandering albatrosses, *Diomedea exulans* Linnaeus, breed in the interior of the island, and parts are said by Waite (1909) to be riddled by the burrows of mutton birds, though neither he nor Peters (1931) records *Puffinus griseus* from this island. The giant petrel, *Macronectes gigantea*, also breeds on the islands. Cockayne indicates that the birds have less effect on the vegetation of Antipodes Islands than on that of some others of the Subantarctic Islands. He regards the remarkable endemic *Senecio antipodus* as determined in its local distribution by the manuring effect of nesting giant petrels. The endemic pipit, *Anthus*

steindachneri Reischek, feeds largely on flies breeding in penguin droppings (Waite, 1909).

Aston (1909) described a peculiar red earth occurring on the ledges of the cliff. It is said to be derived from a red scoria. Analysis gave:

	RED SCORIA	RED EARTH
SiO ₂	41.95%	27.68%
Al ₂ O ₃	13.40	10.48
FeO and Fe ₂ O ₃	15.75	27.40
P ₂ O ₅	2.55	10.70
CaO	9.10	1.50
MgO	5.58	0.79
Mn ₂ O ₃	0.25	tr.
TiO ₂	2.25	0.46
Insol. titanium phosphate	—	8.40
ZrO ₂	—	0.41
Na ₂ O	7.74	2.25
K ₂ O	1.56	0.60
H ₂ O at 110°C.	0.36	4.35
Ign. loss	—	5.00

The phosphate in the scoria is said to be present as titanium phosphate; in the earth the highly insoluble titanium phosphate was apparently estimated separately from such phosphate and titanium as could be brought easily into solution. The insoluble titanium phosphate contained:

TiO ₂	61.82%
P ₂ O ₅	37.1
Indet.	1.08

probably corresponding to 3TiO₂·P₂O₅ which requires:

TiO ₂	62.84%
P ₂ O ₅	37.16

It is evident that not all the phosphate in the original scoria is present as 3TiO₂·P₂O₅. Moreover the ratio of total P₂O₅ to total TiO₂ in the scoria is 1.133, while the ratio of the two oxides in the earth is 2.448. If the titanium is assumed to be the least mobile element determined in the two analyses it is clear that the earth is much enriched in phosphate over the parent material. All other elements determined seem to have been lost to some extent from the scoria, iron least, magnesium and calcium most. While it is very probable that the titanium phosphate is a residual material derived from the scoria, it seems reasonable to suppose that the excess phosphate above that implied by the ratio of titanium to phosphate in the parent material is added from the excreta of birds frequenting the cliff. Morgan (1928), who gives no discussion of details, concluded that the formation of the red earth represented biological phosphatization. Although this is probably true only of the phosphate not in combination with titanium, it is worth noting that titanium phosphates seem to be unknown elsewhere in nature.

ISLANDS IN THE VICINITY OF BASS STRAIT AND OFF TASMANIA

The temperate seas of Victoria and Tasmania are frequented by various birds that breed in immense colonies on certain islands, notably in Bass Strait. On some of these islands a little guano has been worked. The quantity present is clearly small in relation to the number of birds, but it is rather remarkable that any deposits of value should have been found in such temperate regions. The rainfall is fairly low, probably between 500 and 700 mm. per year, for all the localities to be considered. With a mean temperature of about 13.3° C., such a rainfall is by no means biologically ineffective, but in places it is evidently not mechanically sufficient to wash away the whole of the annual guano deposit, even when this is deposited on localities that

do not seem to be physiographically suitable for its retention. It is noteworthy that the coastal deposits of Tasmania all were found along the drier eastern coast of that island, and that the only island on the western coast ever operated as a guano island produced a product that proved not to be guano.

The "Sailing directions for Australia" (United States Hydrographic Office, 1931) state that coastal currents, dependent largely on tide and wind, may be very strong locally; some vertical mixing may therefore be expected.

Mattingley (1934) indicates *Morus s. serrator* (Gray) as the most important guano bird in the region, but considers that the albatross *Diomedea c. cauta* (Gould) and the

cormorant *Phalacrocorax fuscescens* (Vieillot) locally produce a small amount. Mattingley's remarks obviously apply only to Bass Strait and its vicinity and cannot be taken to apply to other Australian guano islands, though he claims that *Sula sula* produces practically no guano at its nest, nor *S. leucogaster* while brooding its young. He claims that gulls, terns, and pelicans may whiten rocks, but that most of the deposit is washed away. His suggestion that the Peruvian guano birds should be introduced to Australia is not likely to be taken very seriously.

Twelvetrees (1917) considered that phosphatization of shell limestone, presumably of relatively recent origin, which may lie along the present shore line is responsible for part of the phosphatic deposits of this region, but only on King Island and perhaps to a small extent on Flinders Island does the existence of this process seem to be substantiated.

LAWRENCE ROCKS

LATITUDE 38° 30' S., LONGITUDE 141° 40' E.

About 1.6 kilometers east of Cape Sir Grant. The important bird colonies on these rocks were examined by W. Macgillivray, whose observations were communicated to North (1912). The main rock has high ground at either end, with a central depression. On the northern elevation several feet of loose guano were found. This was overgrown with clumps of *Mesembryanthemum* riddled with hundreds of burrows of the fairy prion or snow bird, *Pachyptila turtur* (Kuhl) (sub *Prion ariel*). Less numerous mutton birds, *Puffinus tenuirostris*, and many fairy penguins, *Eudyptula minor novaehollandiae* (Stephens), were also present. The penguins lived only in the lower part of the guano and on the slope below the deposit. Mattingley (1908) who also visited the colony says that fairy prions bred in loose soil between the two rocky summits and that, owing to competition with penguins, they could use only the fringe of the loose area. *Morus serrator* occupied the southern elevation, but no indication is given of its effectiveness as a guano producer.

According to Crowther (1939) the Lawrence Rocks were exploited as early as 1854, three little ships being involved in the trade.

The guano sold at Hobart Town for £8 per ton. The high price suggests that the material was supposed to be nitrogenous.

COUNCILLOR ISLAND

LATITUDE 39° 50' S., LONGITUDE 144° 18' E.

Off the east coast of King Island, marked on a map given by Nye (1928) as producing guano. No details are available.

ELEPHANT ROCKS

Also off the east coast of King Island, yielded an impure phosphatic guano containing 11% P_2O_5 according to Twelvetrees (1917), who adds that he was informed by H. M. Rivett-Carnac that anywhere along the west coast of King Island layers of redeposited lime with up to 10% P_2O_5 occur. The same informant considered Pyramid Rock between King Island and Hunter Island a likely source of guano and adds that on Flinders Island 2% to 5% P_2O_5 occur in limestone, presumably of relatively recent origin.

BREAKSEA ISLANDS

On the west coast of Tasmania, worked by Crowther and the product exported to England, where it proved not to be guano (Crowther, 1939).

ALBATROSS ROCK

LATITUDE 40° 22' S., LONGITUDE 144° 40' E.

In the Hunter group, a steep rock about 1.4 kilometers long, 450 meters wide, and 38.1 meters in height, the site of a colony of *Diomedea c. cauta*. According to North, the nests are circular mounds of sand, tussock grass, and guano. Mattingley estimates that a ton of guano may be present. The accumulation, however, is obviously so small that the locality can hardly be regarded as a guano island.

MOUNT CHAPPELL ISLAND

LATITUDE 40° 16' S., LONGITUDE 147° 56' E.

An island 2.4 kilometers long and rising to a height of 199 meters, apparently yielded a little guano in the nineteenth century. Both Dr. W. L. Crowther and a Mr. Askunas attempted to work the island without licenses. The latter obtained possession by means of a

false document supposed to have been sealed with a label from a pickle bottle and impressively read aloud by a man dressed as a constable. Only 300 tons of guano were obtained, from the site of a cormorant (presumably *P. fuscescens*) colony (Crowther, 1939).

PELICAN ISLAND, IN FRANKLIN SOUND
ABOUT LATITUDE 40° 20' S., LONGI-
TUDE 148° 00' E.

Described by Campbell (1901) as the site of a large colony of *Pelecanus conspicillatus* Temminck which colony was destroyed by removing the guano deposits. The exact position of the island cannot be identified from the "Sailing directions for Australia," volume 2.

CAT ISLAND

LATITUDE 39° 55' S., LONGITUDE 148° 22' E.

One of the three Babel Islands, so named on account of the discordant and various notes of the innumerable birds upon them ("Sailing directions for Australia," United States Hydrographic Office, 1931). It is in the Furneaux group at the eastern end of Bass Strait and is a well known breeding place of the Australian gannet, *Morus s. serrator*. North (1912) quotes observations on the colony communicated to him by H. P. Ashworth and by E. D. Atkinson. Ashworth noted about 2500 birds on nests; these nests were constructed on a base of clay and guano, the actual nest being of seaweed, Bryozoa, and twigs. Atkinson says that the piling of new nests on the top of old produces a typical guano deposit. The colony of Australian gannets has declined during the present century; Mattingley (1934) noted about 2000 pairs, and Anderson and Anderson (1936) but 800 to 1000 birds. The latter observers concluded that the decline was due to human disturbance of the birds, for when the island is visited the gannets leave their nests unguarded and so liable to depredation by the gull *Larus pacificus*. According to Crowther (1939) Mr. Askunas applied for a license to remove guano from Cat Island about 1860, but the license does not appear to have been granted. Ashworth, however, indicates that exploitation had taken place early in the present century and noted a large heap of guano waiting to be removed that was said

to have lain for several years near the landing place. This implies a rather stable material from which the organic matter had no doubt largely disappeared. Mattingley (1934) estimated that there were only 5 to 6 tons of guano on the island, but much had doubtless been removed in the early years of the present century.

Other islands in the Furneaux group are of economic importance as they support colonies of the mutton bird, *Puffinus tenuirostris*, but this burrowing species does not appear to produce any significant deposit of guano.

WHITE ROCKS, OFF ISLE DES PHOQUES

LATITUDE 42° 35' S., LONGITUDE 148° 08' E.

These, together with Green Island at latitude 42° 50' S., longitude 148° 05' E., and two Doughboy Islands at latitude 42° 55' S., longitude 147° 37' E., are marked by Nye (1928) on a map showing the distribution of guano deposits around Tasmania, but no details are available. None of these localities is mentioned by these names in the "Australia pilot." Twelvetrees further mentions White Rocks and Slopen Island. It is probable that in all these cases the amount of material present was small. Nye states that the guano islands of his map, namely, White Rocks, Green Island, and the two Doughboys, with an island (presumably Cat Island) in the Furneaux group, and Councillor Island off King Island, are mostly granite and that no phosphatic alteration has occurred. In spite of this statement, it may well be worth while looking for taranakite in such localities.

Twelvetrees states that two samples of phosphatic material from White Island contained 3.10% and 13.80% P_2O_5 , respectively, while the Slopen Island material contained 13.65% P_2O_5 . This last island is formed of diabase, Permo-Carboniferous mudstones, and Mesozoic sediments. Twelvetrees supposed that the calcium of the phosphatic deposit was derived from the mudstones, but it is clear from innumerable other occurrences that bird droppings contain enough calcium to produce calcium phosphate beds.

According to Ulrich (1870) vivianite, $Fe_3P_2O_8 \cdot 8H_2O$, occurred on several of the guano islands of Bass Strait. No details of the occurrences are given, but the mineral

was presumably below or associated with the guano. Although vivianite is a rather common mineral in the reduced parts of the bio-

sphere, as in certain soils and peat deposits, it does not appear to have otherwise been recorded from guano deposits.

ISLANDS OFF THE CENTRAL AND WESTERN PARTS OF THE SOUTH COAST OF AUSTRALIA

A number of islands along the coast of south Australia appear to have yielded limited amounts of phosphatic guano. The chief information available is derived from a report by Jack (1919) who lists all the islands for which guano licenses were granted, without indicating in most cases whether material was actually found and removed from them. Only in the cases of Marum Island, the Bickers Islets, and Brothers Island was he able to quote any details on analyses. Apart from Jack's report the only available information refers to islets on the Recherche Archipelago in the western part of the southern coast of Australia. Where any detailed information exists it seems clear that the main deposit, though presumably post-Pleistocene, does not represent contemporary phosphatization. It is highly probable that further study of these localities would yield information of considerable climatological and oceanographic interest.

According to Jack, the localities on the coast of South Australia, from Kangaroo Island to Denial Bay, yielded 15,000 to 20,000 tons of phosphatic material to Messrs. A. W. Sandford and Company, who worked the islands for 20 years, presumably at the end of the nineteenth century. Such material usually contained 25% to 42% P_2O_5 and 1% to 3% NH_3 . The highest phosphate contents must refer to exceptional samples, probably containing monetite. The total yield must have been equivalent to about 2000 tons P.

BANDON ROCK AND GODFREYS ISLAND, NEAR ROBE

LATITUDE $37^{\circ} 05' S.$, LONGITUDE $139^{\circ} 45' E.$

These appear to be the easternmost localities mentioned as licensed.

ALTHORPE ISLANDS

LATITUDE $35^{\circ} 23' S.$, LONGITUDE $136^{\circ} 05' E.$

A group of three islands of which the largest is about 1 kilometer in diameter, flat

topped, and 93 meters high. According to the "Australia pilot" (United States Hydrographic Office, 1930b), the summit is frequented by penguins and mutton birds.

PELICAN LAGOON, KANGAROO ISLAND

LATITUDE $35^{\circ} 47' S.$, LONGITUDE $137^{\circ} 47' E.$

A shallow lagoon about 5.6 kilometers long and 2.4 kilometers wide joined to Eastern Cove by a channel called American River. Six islands in the lagoon and channel are said to have been licensed. Jack indicates that the islands were actually worked by Messrs. A. W. Sandford and Company, who began their guano operations on this coast at these localities presumably in the late nineteenth century. Since this concern exploited the islands of Pelican Lagoon first, it is reasonable to suppose that they were richer in guano than other localities visited later.

Bushy Island, Beatrice Island, and other islets on a sand spit extending southeast from Cape Rouge on the east coast of Kangaroo Island and the Casuarina Islets, two bare rocky islands south of Cape Couedie (the southwestern point of Kangaroo Island), are also said to have been licensed.

SIR JOSEPH BANKS ARCHIPELAGO

LATITUDES $34^{\circ} 29' - 34^{\circ} 43' S.$, LONGITUDES $136^{\circ} 13' - 136^{\circ} 17' E.$

A group of about 20 islands. Reevesby and Spilsby are said by the "Australia pilot" to be the only islands on which water can be obtained and to have vegetation higher than low bushes. Jack indicates that licenses were granted for Blyth Island, Dalby Island, Hareby Island, Kirkly (or Kirkby) Island, Langton (or Milne) Island, Lusby Island, Marum Island, Partney Island, Reevesby Island, Sibsey Island, and Winceby Island. Messrs. A. W. Sandford and Company are said to have worked the Sir Joseph Banks group in their last 20 years of exploitation of the south Australian phosphatic guano is-

lands. The deposit on Marum Island alone of the islands of the group has been described (H. Jones *in* Jack, 1919).

Marum Island is about 460 meters long and 90 meters wide and rises to a height of 9 meters above sea level. It is covered with darkish soil 15 to 45 cm. thick, composed chiefly of sand and guano. In a trench at the site of the principal guano digging in the southeast part of the island a stratum of rock phosphate 30 to 90 cm. thick and 12 meters wide was discovered. This perhaps extended some way through the surface deposits of the island. A cave at the northeastern end about 30 meters long, 12 meters wide, and a little over 1 meter high contained a fair amount of guano.

The following determinations of phosphate and nitrogen are given:

	P ₂ O ₅	N
Limestone cap, 2 feet	1.6%	—
Limestone and rock phosphate	13.6	—
Rock phosphate, 3 feet thick	16.1	—
Guano, 1-2 feet	13	0.23%
Guano and sand, 1 foot	7.8	0.76
Guano, southeast end, 1 foot	21.4	0.66
Guano, central part of working, 1.5 feet	11.0	0.41
Guano, central part of working, 1 foot	15.4	0.55
Guano, northwest end, 1 foot	13.2	0.81
Limestone cap, 5 inches, northwest of working	0.6	—
Guano and sand, large cave	7.5	0.55
Guano, east cave in workings	12.1	0.38
Guano, south cave in workings	12.2	1.30

It seems probable that the deposit has, at least in places, a calcareous overburden and is probably not the result of a modern colony.

OTHER ISLANDS AT THE ENTRANCE OF SPENCER GULF AND OFF PORT LINCOLN (LATITUDE 34° 43' S., LONGITUDE 135° 51' E.) AND LOUTH BAY

According to Jack the following islands were licensed: the Bickers Islets; Boucart Island, Louth Bay; Dangerous Reef; Donnington Island; Duffield Island, Louth Bay; English Island; the Gambier Islets; Grindal Island; Hopkins Island near Thistle Island; Lewis Island near Thistle Island; Louth Island, Louth Bay; Neptune Island near Thistle Island; Rabbit Island, Port Lincoln;

Rabbit Island, Louth Bay; Rokely Island, Louth Bay; Smith Island near Thistle Island; Taylor Island; Ward's Rock near Wedge Island; and Williams Island, Cape Catastrophe. The last named is said by the "Australia pilot" to be a breeding place of mutton birds and *Cereopsis*. Curta Rocks and Liguanea Islands off Sleaford Bay, to the west of Cape Catastrophe, are also listed by Jack as having been licensed.

Details of the phosphatic deposits on these islands are available only for the Bickers Islets. North Bickers Islet is described as about 460 meters long, 370 meters wide, and 15.3 meters high. The general structure is said to resemble Marum Island save that granite protrudes in places presumably through a superficial limestone layer. Two main workings existed, one in soft material with large granite boulders, the other in rock phosphate up to 60 cm. thick. The phosphatic material of South Bickers Islet is said to have been more sandy than that of North Bickers Islet. At least 272 tons of guano are known to have been obtained. The following analytical data are reported:

	P ₂ O ₅	N
East side of digging, No. 1	8.8%	—
East side of digging, No. 1	11.0	—
West side of digging, No. 1	16.2	—
West side of digging, No. 1	29.4	—
Guano 6 inches thick	22.2	0.40%
Guano 6 inches thick	12.3	0.66
From all-over face, including limestone	9.8	—
From shaft 8 feet deep, guano	16.1	0.48
From top of shaft	7.4	0.48
North of works, sand and guano	4.3	0.51
East end of island, sand and guano	1.2	0.75
Phosphate rock, present (i.e., at time of report) working	21.1, 21.9	—
Capping	3.7	—
S. Bickers Islet, limestone	1.9	—
S. Bickers Islet, limestone and guano	5.3	1.04

As at Marum Island there appears to have been a surface limestone over part of the phosphatic deposits.

ISLANDS OFF COFFIN BAY

Brothers Islands, Greenby Island, the Hummock, and Rocky Island (latitude 34°

49' S., longitude 134° 43' E.) are listed as having been licensed. Of these the deposit on Brothers Islands is described in a report by George (1908) reprinted by Jack. The Brothers Islands are two islets, the larger one to the west being about 140 meters long, 80 meters wide, and 12 meters high, the smaller one about 40 meters long, 20 meters wide, and 4.6 meters high. The islands are said to consist of a yellow gray limestone covered with a superficial marine limestone full of cavities. At the west end of the larger island a small depression apparently representing the back of a cave was filled with bone breccia. Fragmented bones of giant kangaroo, small mammals, and birds were cemented together with calcareous material, and the limestone rock in the vicinity was slightly phosphatized. On the north side of the island near the water, crevices in limestone were filled wholly or in part with phosphate, and much sandy guano was removed from such cavities. The bone breccia extended to 3 meters below the surface, and in one case the limestone on the lower side of a cave-like crevice was phosphatized to a thickness of 60 cm. The phosphate contents of some of these materials were determined as follows:

	P ₂ O ₅
Breccia, west end	25.0, 27.1%
Rock phosphate, north end	25.6, 31.3
Limestone	1.0, 2.0

ISLANDS IN THE EASTERN PART OF THE GREAT BIGHT FROM COFFIN BAY (LATITUDE 34° 27' S., LONGITUDE 135° 18' E.) TO DENIAL BAY (LATITUDE 32° 12' S., LONGITUDE 133° 35' E.)

Jack lists, as having been licensed, the following islands:

Flinders Island and the Waldegrave Islands in the Investigator group
Islands designated D, E, F, and G in Venus Bay
Franklin Island and Olive Island in Strehay Bay
Eyes Island and Thompson Island near Laura Bay Point, in Smoky Bay
Evans Island and Goat Island in Denial Bay

The Venus Bay islands are stated to have been exploited when the Kangaroo Island localities were exhausted, and the Waldegrave Islands after the Venus Bay islands had been worked. When this part of the coast was worked out attention was given to the Sir Joseph Banks Islands. No other details are available.

THE RECHERCHE ARCHIPELAGO

LATITUDES 34° 02'–33° 43' S., LONGITUDES 121° 36'–124° 04' E.

This consists of a vast number of islands and reefs along the southern coast of Australia west of the Great Bight, off a region receiving 500 to 750 mm. of rain per annum.

Maitland (1928) says phosphate has been known since 1904 on some of the islands. The two islands specifically mentioned are Salisbury Island, latitude 34° 21' S., longitude 123° 33' E., and Christmas Island, of which the position has not been ascertainable. The only information available about the Salisbury Island deposit is contained in a somewhat enigmatical statement by Maitland that the material contained 6% to 30% P₂O₅, a little nitrogen, and 75% to 90% CaCO₃.

The Christmas Island deposit is better known. The island is formed of ancient crystalline rocks, biotite-granite, and gneiss with pegmatite dykes. On this material lies a series of cream-colored limestones and sandstones with varying thickness of dark shelly limestone at the base, the whole covered with an irregular deposit of travertine and an overburden of sand or soil of 60 cm. average thickness. The basal bed and travertine are phosphatized, analyses giving 3% to 23.58% P₂O₅ and 1% to 2% N. The phosphatized deposit is said to occupy a fairly large area. The stratigraphy suggests that the phosphatization is not contemporary. The full elucidation of the deposit is probably of great paleoclimatic interest. Stutzer (1932) confuses this locality with Christmas Island in the Pacific Ocean.

ISLANDS OFF THE WEST COAST OF AUSTRALIA

A series of islands along the western coast of Australia have yielded guano. The Lacépède Islands, Shark Bay, and Houtman's Abrolhos deposits were the most important, but evidence of guano beds on six other islands or island groups has been recorded.

CLIMATOLOGY

The temperatures along the coast are lower than in the interior, but the northern islands may be regarded as tropical or subtropical with mean monthly summer temperatures above 22.5° C. and mean monthly winter temperatures little if any below 17.5° C. The southern islands are in general about 5° C. cooler than the more northern. The whole coast is fairly dry, with a seasonal rainfall, which in the southern part of the region occurs in winter, in the northern part in summer. In the region of minimum rainfall, such rain as occurs is mainly in winter, but on the northern border of the dry zone of about 250 mm. per year some summer rain also seems to occur (Taylor, 1920). The mean annual precipitation is minimal between about latitudes 24° S. and 26° 30' S., in which region less than 250 mm. per year are recorded. In this limited region there was only one deposit, not adequately located, in Shark Bay. Farther north, entering the region of increasing summer rain, Beagle Island and the Montebello Islands probably have between 250 and 500 mm. per annum, the Lacépède Islands between 500 and 750 mm. per year (cf. Taylor, 1920, fig. 120). Most of the other northern localities, some of which are far removed from the coast, doubtless have a rainfall between 750 and 1000 mm. per annum. The most southern islands on the west coast, south of the zone of minimum rainfall, appear to receive about 500 mm. per annum.

OCEANOGRAPHY

In the southern summer the main water movements off the western coast of Australia are northward, but a large eddy develops south of Shark Bay with its center at about latitude 28° 30' S. Farther south Willimzik (1929) indicates considerable off-shore movement of water. In the southern winter a complicated pattern appears to be established

with eddies off the northern part of the coast, and according to Schott (1935) coastal upwelling of cold water occurs between latitudes 19° S. and 23° S. No adequate information on the effect of hydrography on the productivity of the region appears to be available. It is clear, however, from Townsend's (1935) maps that a very considerable concentration of sperm whales occurred in the region off the western coasts of Australia, between latitudes 17° S. and 31° S. in the southern winter and between latitudes 23° S. and 38° S. in the southern summer. Two populations, however, may have been involved, one remaining off the southwest coast between latitudes 36° S. and 38° S. throughout the year and the other moving north and south off the western coast.

ORNITHOLOGY

The ornithology of the individual localities has not been so well studied as would be desirable, but as far as can be ascertained terns are the most important guano birds. This is explicit in Walker's account of Adèle Island, on which the only bird colony mentioned as producing guano was that of *Sterna bengalensis torresii* (Gould) (sub *S. media*). Farther south, as is apparent from the accounts given by North (1913-1914), the most important guano birds on Houtman's Abrolhos are likely to have been sooty terns, *S. fuscata serrata* Wagler, and noddies, *Anous stolidus gilberti* Mathews.

TOTAL QUANTITY OF GUANO

Maitland (1928), who has given the best account of the phosphatic guano of this region, states that exploitation began in 1874. Most of the guano was exported from 1876 to 1904, after which the deposits were reserved exclusively for Australian use. No records were kept during the early days of exploitation, but it is known that 118,530 tons (presumably English, equals 120,200 metric tons) were removed prior to the end of 1904, and 13,997 (=14,200 metric tons) between 1905 and 1915. Little material was evidently left at that time. The total amount removed was therefore at least 134,500 metric tons, which would correspond to about 40,000

metric tons P_2O_5 . If the figures for the actual removals given by Maitland be added, a slightly different value is obtained:

	TONS
Ashmore Shoals, Jones, Lesueur, Stewart, and Black Hawk Islands	2,577
Browse Island	23,177
Lacépède Island	37,226
Houtman's Abrolhos	56,025
	119,005

The total amount originally present was, however, certainly greater than this estimate, for the latter does not include 50,000 tons left on the first group of islands in 1884, while the total original estimate of the reserve for the three island groups of Houtman's Abrolhos is 100,600 tons. These estimated quantities may have been excessive. The total quantity must, however, have been between 120,000 and 210,000 tons, corresponding to a quantity of P_2O_5 between 36,000 and 63,000 tons.

DESCRIPTION OF THE ISLANDS

THE ASHMORE OR SADIE ISLANDS

LATITUDES $12^{\circ} 8' - 12^{\circ} 25' S.$, LONGITUDES $123^{\circ} - 123^{\circ} 30' E.$

Three low islets not over 3 meters high. The largest, West Islet, is about 1.1 kilometers long and 640 meters wide. The islands are said to be of sand covered with coarse grass. These islets were worked for phosphate in the latter part of the nineteenth century (Maitland, 1928; Elschner, 1913; Ullmann, 1911), but no details are available.

JONES ISLAND

LATITUDE $13^{\circ} 45' S.$, LONGITUDE $126^{\circ} 01' E.$

A small island off Cape Bougainville, 550 meters long and 3 meters high, encircled by a reef. It is said to be sandy ("Australia pilot," United States Hydrographic Office, 1920b). It is mentioned by Maitland as a former source of phosphatic guano, and an analysis by A. Grimm is given by Ullmann (1911):

H_2O	7.93%
Ign. loss	10.92
CaO	42.86
Fe_2O_3	0.33
Al_2O_3	0.54
P_2O_5	34.22
CO_2	1.87

STEWART ISLAND

LATITUDE $13^{\circ} 45' S.$, LONGITUDE $126^{\circ} 50' E.$ ¹

This island, Lesueur Island (latitude $13^{\circ} 51' S.$, longitude $127^{\circ} 16' E.$), and Black Hawk Island (of which the position cannot be ascertained from available sources) are listed, with Ashmore Island and Jones Island, by Maitland (1928).

BROWSE ISLAND

LATITUDE $14^{\circ} 07' S.$, LONGITUDE $123^{\circ} 33' E.$

A coral island about 0.7 kilometers long and 6 meters high at the northern end, where there is a slight plant cover. The island is surrounded by a reef. Elschner (1913) describes the deposit from apparently unpublished accounts by Captain Roggenburg and Captain Rohtbar. The central plateau of the island, which has a general height of 3 meters, is covered with soil 15 cm. thick at the edge, 50 cm. thick at the center. This supports a plant doubtfully identified as *Portulaca*, and is composed of weathered coral and decaying plant matter. Below this is a layer of so-called stone guano, apparently phosphatized coral; beneath this is a layer of guano evidently more friable than the stone guano. Stone guano and guano alternate again below this, three to six layers being present of thickness 8 to 40 cm. The thicker layers are probably central and may represent a lagoon filling.

Analysis by Gilbert (*in* Heiden, 1887) gives:

H_2O	15.00%
Org.	10.30
Fe_2O_3	0.32
CaO	39.94
MgO	0.21
Na	0.06
P_2O_5	31.40
SO_3	1.01
CO_2	1.48
F	0.34
Cl	0.08

¹ The "Sailing directions for Australia," volume 4 (United States Hydrographic Office, 1932b), gives no Stewart Island in this vicinity. The Stewart Islands are entered in the index with reference to a page dealing with Cambridge Gulf farther west, but no reference to the islands appears on the page. The bearings given are those of the Times Atlas. There is a Stewart Island farther south in Mary Anne Passage, but from the arrangement of Maitland's localities the northern one is certainly indicated.

Maitland states that 23,177 tons of guano were removed prior to the end of 1886, but that the amount of rock phosphate taken was not officially estimated.

WHITE ISLET

Described in the "Australia pilot" (United States Hydrographic Office, 1920b) as a low islet covered with guano. Maitland (1928), confirming the occurrence, states that the material contains from 7% to 29% P_2O_5 and from 1% to 3% N.

ADÈLE ISLAND

LATITUDE $15^{\circ} 31\frac{1}{2}'$ S., LONGITUDE $123^{\circ} 9\frac{1}{2}'$ E.

A low, flat island about 3.2 kilometers long, 1.4 kilometers wide, and 2.4 meters high, surrounded by a reef, lying 72 kilometers north of the entrance of King Sound, north-west Australia. The island is sandy and covered with grass and beds of *Ipomaea*. A wild bean (*Phaseolus*) and an orange *Sida* are also conspicuous. The soil is apparently sand somewhat mixed locally with inferior guano (Walker, 1892). *Sula leucogaster plotus* and *S. dactylatra* both occur, constructing nests of seaweed. Among the *Sida* bushes *Phalacrocorax varius* (Gmelin) was breeding, strewn dead fish around. *Fregata minor* occupied a strip of *Ipomaea* with a little grass, in the middle of the island. A colony of *Sterna bengalensis torresii* (Gould) (sub *media* Horsfield) occupied an open bare area and was producing a patch of indifferent guano. Another better deposit, described as 6 to 24 meters thick, at the southeast end of the island was described to Walker but not discovered by him. Maitland (1928) says that the deposit contains 33% P_2O_5 and 1% N.

LACÉPÈDE ISLANDS

LATITUDE $16^{\circ} 51'$ S., LONGITUDE $122^{\circ} 06'$ E.

A group of four low islands of sand and coral surrounded by a reef. Guano was exported from these islands during the nineteenth century. According to the "Sailing directions for Australia" (United States Hydrographic Office, 1932b) the deposit was on Middle Island, which is about 1.6 kilometers long, 0.6 kilometers wide, and 1.5 meters high. Elschner (1913) states that this island can be entirely submerged, as during a

cyclone in February, 1878. He indicates that birds breed here in the middle of March.

Analyses (I) by Gilbert (Ullmann, 1911), (II) by Chevron (1880), (III) by Voelcker (1878b) are as follows:

	I	II	III
H ₂ O	12.40%	6.78%	7.80%
Org.	9.92	10.54	11.38
Fe ₂ O ₃	0.75	1.61	0.39
Al ₂ O ₃	—	—	0.74
CaO	40.80	41.03	40.70
MgO	0.93	0.55	1.26
K	—	0.17 = 0.21 K ₂ O	0.50
Na	0.06	0.15 = 0.26 Na ₂ O	
P ₂ O ₅	33.64	35.22	34.62
SO ₃	0.10	0.50	0.88
CO ₂	0.86	1.05	0.79
SiO ₂	—	1.88	0.94
F	0.77	tr.	—
Cl	0.10	0.42	—
N	—	0.65	0.63

Voelcker also gives four less complete analyses:

H ₂ O organic	16.32%	19.01%	21.15%	19.85%
CaO	42.22	40.71	40.29	40.85
P ₂ O ₅	35.88	34.04	33.16	33.87
Insol. SiO ₂	1.35	1.75	0.01	1.02
MgO, Fe ₂ O ₃ , Al ₂ O ₃ , etc.	4.23	4.49	4.39	4.41

The material analyzed seems to have been very uniform. Maitland (1928) says that the Lacépède Islands produced 27,226 tons but are now exhausted.

THE MONTEBELLO ISLANDS

LATITUDE $20^{\circ} 30'$ S., LONGITUDE $115^{\circ} 30'$ E.

Said by Meise, on the basis of a private communication from Nevermann, to have guano or phosphate deposits.

BEAGLE ISLAND

LATITUDE $21^{\circ} 10'$ S., LONGITUDE $115^{\circ} 36'$ E.

Also termed Great Sandy Island in the "Sailing directions for Australia," described as a narrow, sandy island, 1.65 kilometers long, and 11.3 meters high, covered with stunted bushes. Maitland (1928) states phosphate containing 14% P_2O_5 and 2% N has been obtained from Beagle Island. The record presumably refers to this locality though there are two Beagle Islets, farther south, in latitude $29^{\circ} 49'$ S., longitude $114^{\circ} 51'$ E.

SHARK BAY

LATITUDES 24° 45'–26° 24' S., LONGITUDES 113° 10'–113° 51' E.

Shark Bay guano was well known in nineteenth century commerce, but no certain information is available as to its origin. According to the "Sailing directions for Australia," Guano Islet is a small island southwest of Quoin Bluff, Shark Bay. Pelican Island has a colony of *Pelecanus conspicillatus* Temminck (North, 1912), but nothing is recorded as to guano production. According to a letter from H. Merivale dated May 26, 1851, 4000 tons of shipping were waiting to load at Shark Bay, but according to Capt. J. Everard Home, writing on April 26, 1852, on board H.M.S. "Calliope" at Hobart Town, the deposit was exhausted at the date of writing and the military detachment stationed at Shark Bay to keep order had been withdrawn (Great Britain, Parliamentary Sessional Papers, 1857).

Nesbit gives three analyses:

H ₂ O	14.47%	19.80%	11.08%
Organic	7.85	14.55	18.87
SiO ₂	14.47	7.25	8.45
Ca ₃ P ₂ O ₈	29.54	50.75	59.05
Alkalis	33.06	7.65	2.55
N	0.35	0.77	0.70

The first sample is probably contaminated with sea salt. The material is obviously a typical phosphatic guano. Ullmann in an incomplete analysis gives 15% H₂O and 23.59% P₂O₅; 4% to 6% CaCO₃ is also recorded.

HOUTMAN'S ABROLHOS

Comprise three groups of islets, named from north to south the Wallabi group, Easter group, and the Pelsart group. These islands are of some historical interest as they were discovered as early as 1527 by Menezes. All are of limestone containing calcareous algae, Foraminifera, and echinoderm fragments; Maitland (1928) does not mention corals. An analysis given by Maitland records 87.87% CaCO₃ and 7.53% MgCO₃, suggesting lithothamnium reef. Absence of quartz in the limestone suggests formation some distance from land. The larger members of the Wallabi group are 9 to 15 meters high, but this elevation would seem more likely due to sand hills rather than to elevated reef.

The outer eastern members of the Easter and Pelsart groups are said by the "Sailing directions" to consist of mere ridges of dead coral and shells, while the inner islets are flat blocks of limestone about 1.5 meters high, covered with light sandy or guano soil and bearing a stunted plant cover.

Much information on the birds of Houtman's Abrolhos is scattered through North's (1912–1914) magnificent treatise on the nidification of Australian birds. Rat Island, the largest island of the Easter group, is recorded as the home of innumerable sooty terns (*Sterna fuscata serrata*) and noddies (*Anous stolidus gilberti*). A photograph of the noddy nests among low herbaceous vegetation and grasses indicates little or no contemporaneous deposition of guano, but it is not improbable that the sooty terns occupied barer areas and that the island was less vegetated at the time that guano was accumulating. The same two species occupied Pelsart Island, but apparently the Rat Island colony was more extensive than that on Pelsart Island. A large colony of *Sterna gracilis* occurred on Pelsart Island, large numbers of *S. bergii* on both Pelsart and Wooded Islands, on the eastern side of the Easter group. *Anous tenuirostris* bred in the extensive mangrove stands of Wooded Island. The available information suggests ecological succession, Rat Island being in the earliest stage, and Wooded Island, extensively surrounded by mangroves, in the latest. An important colony of the shearwater, *Puffinus assimilis tunneyi* Mathews, is also known to occupy the islands.

A more recent account by Sandland (1937) indicates that the bird colonies of Rat Island have suffered greatly from feral cats, the descendants of animals introduced by the guano workers. The Pelsart Island colonies of sooty terns and noddies are, however, flourishing, occupying 12 acres, noddies occurring in the central five acres and having exclusive possession of two acres. Sandland says three or four acres of the island had been scraped for guano.

Maitland states that 18 islets of the Wallabi group, namely, West Wallaby, Pelican, North and South Pigeon, and associated small islets, had 10 to 43 cm. of guano, and that this group yielded 38,088 tons. Nine of

the 14 Pelsart Islands, namely, Pelsart itself, Gun Island, and seven small islets, had 18 to 33 cm. of guano and yielded 38,088 tons. Four of the 10 islands of the Eastern group had 10 to 68.5 cm. of guano and yielded 13,944 tons.

Very little phosphatization of the underlying limestone occurred. On West Wallaby a crust of highly phosphatic rock, not over 3 mm. ($\frac{1}{8}$ inch) thick coated the rock below the guano, but underneath this crust the limestone normally contained but 1% or 1.5% P_2O_5 . An exceptional sample, however, with 6.28% is recorded. Such an amount is low compared with the P_2O_5 content of the almost completely phosphatized coral rock known on some Pacific islands.

Analyses of Abrolhos guano, by A. Grimm (I) and by H. Gilbert (II) have been published by Ullmann (1906):

	I	II
H ₂ O	4.48%	10.10%
Ignition loss	—	6.20
Nitrogen	0.38	—
CaO	43.20	—
(Al,Fe) ₂ O ₃	3.10	1.67
MgO	—	0.97

P ₂ O ₅	31.80	33.67*
F	—	1.25

* Or 32.22% by calculation from the $Ca_3P_2O_8$ content of 70.32%. The material analyzed by Grimm contained 5.56% CaO not accounted for as $Ca_3P_2O_8$; some of this lime doubtless exists as a francolite-like material, but free $CaCO_3$ was no doubt also present in the sample.

UNIDENTIFIED LOCALITY

In addition to the above localities, Ullmann records Shoal Bay as a source of guano-phosphate, entering the name in a list between Bramble Cay and Shark Bay. There are at least four Shoal Bays on the coast of Australia, namely, at the head of Collier Bay (latitude 16° 25' S., longitude 124° 02' E.), near the mouth of the Adelaide River (about latitude 12° 10' S., longitude 131° 00' E.) on the northwest coast, and on Facing Island off Port Curtis (latitude 23° 25' S., longitude 151° 25' E.) and near Point Stephens (latitude 32° 43' S., longitude 152° 11' E.) on the east coast. The first locality, which is described as having low islands, is probably meant, but the attribution is too uncertain to permit inclusion of the record on any map in the present work.

INLAND AVIAN GUANO DEPOSITS IN AUSTRALIA

Two cases of phosphatization of igneous rocks by guano are known from inland localities in Australia.

ELDER ROCK, PARATOO SIDING

LATITUDE 32° 42' S., LONGITUDE 139° 23' E.

This locality, about 256 kilometers north of Adelaide, South Australia, provides a remarkable example of inland biogenic phosphatization (Mawson and Cooke, 1907). A large, vertically sided mass, formed in part of ferruginous quartzite, in part of coarse breccia, containing much magnetite and hematite, stands up about 30 feet above a low-lying level area. In depressed areas on the top, a hard yellowish phosphate was found, and all the cracks and fissures in the rock are filled with the same material. Within the rock a dark chocolate deposit fills chimneys and consists of ferric oxide with much ammonia and nitrate and little phosphate. The yellowish phosphate rock, termed by Mawson and

Cooke paratooite, is also recorded from a lofty quartzite peak 1 mile west of Ajax Mine near Beltana. In both cases phosphatization must have been due to leaching of bird droppings, by restricted precipitation. It is, however, probable that the rainfall was formerly sufficiently high in the vicinity of Elder Rock to convert a near-by creek into a swamp. It is possible that the birds that produced phosphatization frequented this swampy area. At the second locality, recent bird droppings, probably from an eagle, were found passing into material identical with that found at Elder Rock. The lower deposits in the fissures of Elder Rock contain only a trace of phosphate but much ammonium nitrate. At an intermediate level ammonium phosphate is probably present.

Two minerals were recognized as composing the phosphate rock. One, occurring as an isotropic, light yellow, encrusting material, gave on analysis:

	ORIGINAL ANALYSIS	RECALCU- LATED ON SiO ₂ -FREE BASIS
SiO ₂	17.30%	—
Al ₂ O ₃	17.12	20.70%
Fe ₂ O ₃	6.78	8.20
CaO	2.06	2.49
MgO	0.92	1.11
P ₂ O ₅	35.22	42.59
H ₂ O at 120°C.	16.94	20.49
Ignition loss	2.65	3.20
Alkalis, etc., by difference	1.01	1.22

The other mineral occurred as aggregates of globules about 2 mm. in diameter and was yellowish brown on fracture. The spheres consisted of a doubly refracting, indistinctly radially arranged material giving on analysis:

	ORIGINAL ANALYSIS	RECALCU- LATED ON SiO ₂ -FREE BASIS
SiO ₂	36.72%	—
Al ₂ O ₃	7.06	11.19%
Fe ₂ O ₃	24.25	38.43
CaO	2.32	3.68
MgO	—	—
P ₂ O ₅	17.37	27.53
H ₂ O at 120°C.	10.36	16.41
Ignition loss	1.74	2.76

The isotropic material is considered as "a mineral of the evansite type." The anisotropic "is distinctly of the beraunite type, perhaps closely related to globosite." Actually evansite is a basic phosphate, chemically quite different from this material supposedly related to it. The analysis indicates a composition very like that of samples largely consisting of barrandite, (Al,Fe)PO₄·2H₂O. The identification of the other mineral as at least in part a basic hydrous phosphate of iron and aluminum is probable. A further investigation might prove interesting.

LAKE WEELHAMBY

At the eastern end of the Ninghamboun Hills, a large dry salina. It has not been possible to ascertain its exact position, but it

presumably lies in the Ningham district of Western Australia, about latitude 31° S., longitude 117° 30' E. A knoll of serpentine reaching an altitude of 30 meters above the lake level was examined by Simpson (1932). This knoll exhibits three sets of fractures perpendicular to one another. Following the line of the cracks running east and west are two veins about 60 cm. wide and about 9 meters apart. These are filled with multicolored material termed redondite by Simpson, but presumably referable to barrandite. This mineral shows traces of the original structure of the subfibrous actinolite that has undergone alteration. A white chalky mass of chalcedony and a new phosphate, leucophosphorite, were discovered. The new mineral, which evidently contains potassium, was compared to minervite, i.e., taranakite. The type specimen, however, was examined by Bannister (*in litt.*) and proved by X-ray diffraction to be amorphous and not taranakite.

The following analyses are given by Simpson:

	"RE- DONDITE" BROWN	"RE- DONDITE" GREEN	LEUCOPHOS- PHORITE
Al ₂ O ₃	17.81%	20.45%	12.73%
Fe ₂ O ₃	17.66	12.66	32.82
Cr ₂ O ₃	tr.	0.73	0.00
FeO	0.03	0.20	0.00
TiO ₂	0.45	0.21	—
MnO	0.27	0.00	0.22
NiO	—	—	tr.
MgO	0.27	0.00	0.73
CaO	0.00	0.00	tr.
(NH ₄) ₂ O	tr.	tr.	0.09
Na ₂ O	0.19	tr.	0.13
K ₂ O	0.29	0.96	7.88
H ₂ O +	19.82	20.98	12.28
H ₂ O -	1.14	1.97	6.59
P ₂ O ₅	40.23	42.19	26.69
CO ₂	—	0.00	0.17
SiO ₂	1.92	0	0.00
C	—	—	tr.

Simpson supposes the occurrence is due to guano deposited by cormorants that lived around the lake during a pluvial period. Most of the Australian species of *Phalacrocorax* frequent fresh as well as salt water.

GUANO ISLANDS IN THE SOUTH CHINA SEA, IN THE SEAS OF THE EAST INDIAN ARCHIPELAGO, AND IN THE ADJACENT PARTS OF THE INDIAN OCEAN

THE MODERN DEPOSITS to be discussed in the present section are all of minor importance. They occur on some of the numerous raised reefs in the China Sea and on various small islands off Celebes, in the Flores Sea, and south of Timor. In marked contrast to these

unimportant deposits are the extensive phosphate caps on Christmas Island, just south of Java. It is obviously desirable to treat this remarkable locality separately from the other islands.

MODERN GUANO DEPOSITS

Before the modern deposits are described it is desirable to discuss briefly the climatology of the region and then to summarize the relevant oceanographic information. Virtually nothing appears to have been published on the ornithology of the individual localities.

absence of guano islands off the Philippines. The area between Celebes and Flores apparently receives less rain than the Java Sea, and there is also a region of low precipitation marked on Schott's (1931) map to the east of the northeastern end of Celebes (fig. 69).

CLIMATOLOGY

The most conspicuous feature of the region is the seasonal reversal of the dominant wind direction, as high pressures in Central Asia and low pressures over the south Indian Ocean and Australia in the northern winter change to their opposites in the northern summer. The winds, from northeast in the northern winter and from southwest in the northern summer, constitute the monsoons. The northeast monsoon is reinforced by the trade winds and is in general dry; the southwest monsoon, which is in general rather less constant than the northeast, is wet. The rainy season is from May to October in most parts of the region. The rainfall in general increases across the south China Sea from northwest to southeast. The isohyet for 2000 mm. is drawn by Schott as running diagonally across the sea from southwest to northeast. Pratas Island and the Paracel Reefs lie on the drier side of the isohyet; Spratly Island, Amboina Cay, and the other islets off the Dangerous Ground lie on the wetter side of the isohyet. It is, however, by no means certain that much meaning can be attached to the exact drawing of the line. Spratly and the other islets to the southeast are indeed likely to be wetter than the Paracel Reefs, but by how much cannot be at present ascertained.

The Sulu Sea is still rainier than the southeast China Sea, which may account for the

OCEANOGRAPHY

The surface movements of the water are under the control of the monsoons and undergo the same change of direction. In the winter the monsoon drift flows to the south through the China Sea, being most marked in the western part along the coast of China and Indo-China. Schott's (1931) map gives indications of the formation of an eddy in the central part of the sea. The southward monsoon drift turns eastward along the south coast of Borneo and Celebes, passing through the Java and Flores seas into the Sea of Arafura, south of New Guinea. There is also movement through the Sulu Sea southward at this time. During the northern summer when the wet monsoon is blowing from the southwest the pattern of the current system undergoes complete reversal. The water movement is to the north, with an indication of the development of a gyral in the southern part of the China Sea. Schott indicates upwelling off Saigon. At the same time the current is westward in the Java Sea, most of the stream running up the west coast of Borneo to the China Sea in the opposite direction to the flow six months before. The movements in the Sulu Sea and on the western coast of Celebes are, however, still southward. Local movements are doubtless very complex, and regions of increased vertical mixing are likely to be present. The maps indicating the posi-

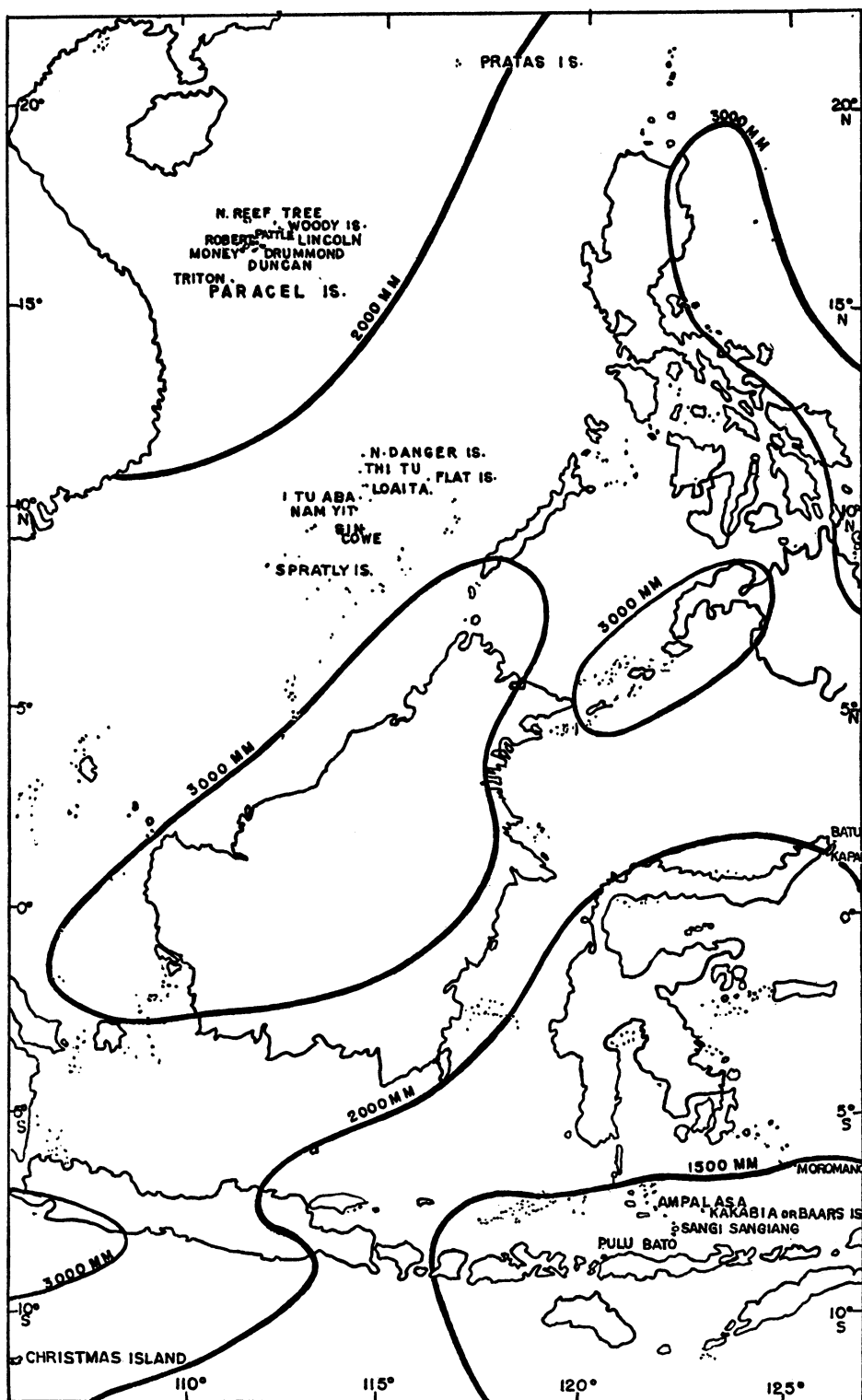


FIG. 69. Map of the East Indies and China Sea to show isohyets.

tions of sperm whale kills (Townsend, 1935) demonstrate the probable existence of high productivity in the Sulu Sea and in the southern China Sea just north of Borneo, east of the northeastern peninsula of Celebes, and between the southern part of that island and Flores. There is some tendency for guano deposits in the southern part of the region to be associated with these apparently productive areas, but in the China Sea the important guano islands are not in the vicinity of whaling grounds.

DESCRIPTION OF THE GUANO ISLANDS

PRATAS ISLAND OR TUNG-SHA-TAO

LATITUDE 20° 42' N., LONGITUDE 116° 43' E.

Situated on the western side of Pratas Reef, a large circular reef with a circumference of about 64 kilometers, a width of up to 3 kilometers, and a large interior lagoon. According to the "Sailing directions for the western shores of the China Sea" (United States Hydrographic Office, 1937a) the island is horseshoe shaped, about 1.6 kilometers long, is sandy and bears trees. Brackish water is said to be obtained by digging in the sand. Aso (1940) states that more than half the island is covered with a fine sandy or earthy phosphate, 6 to 9 cm. thick, though in the level eastern part of the island the deposit is 30 cm. thick. The estimated thickness of 18 feet given by Wong and Hsieh (1928) is obviously a gross exaggeration. Mixed with the sandy phosphate, or forming a layer below it, are nodules of a consolidated cemented phosphatic sand.

The following partial analyses are given by Aso:

	N	P ₂ O ₅	(AL,FE) ₂ O ₃
Sandy	0.21%	6.50%	0.37%
Sandy	0.18	14.46	0.38
Nodule	0.52	22.71	0.51
Nodule	1.00	26.20	0.63

The nodules are said to vary in phosphate content from 17.70% to 28.00% P₂O₅, the mean being 21.28%. The sandy phosphate is much mixed with coral sand and contains 6.10% to 15.0% P₂O₅, the mean being 9.01%. Up to 70% of the phosphate is soluble in ammonium citrate. Nitrogen is always very low, from 0.18% to 1.07%.

An estimate that 180,000 tons of phosphate

were present was originally made, but Aso, who examined the locality, indicates that 50,000 tons is nearer the true value of the reserve. Of this, one-third consisted of the richer lumps, two-thirds of the poorer sandy phosphate. The total quantity of P₂O₅ deposited on the island appears therefore to have been about 8000 tons.

THE PARACEL REEFS

A group of reefs and islets set on a bank in the central part of the south China Sea. According to Clerget (1932) this bank is part of one of a series of terraces of glacial age which have been recognized in the Gulf of Tonkin. The submergence of the bank took place at the close of the last glacial, but subsequently slight emergence has taken place. Chu describes the islands as composed of coral, shells, fish bones, and echinoderm fragments. On Rocky Island this material is cemented together to form a hard stratified rock. The altitude of this island is given as 15 meters. The other islands, composed apparently of less consolidated material, all have altitudes of less than 10 meters above sea level. Clerget indicates that a raised beach at 2.5 meters can be recognized and that this beach bears shells of recent species of mollusks. Several of the islands have central depressions in which water collects.

According to Chu (1929), there are 14 islets, of which he examined four; he reported guano on all of these. Clerget records phosphate on six islands, only one island being common to the two lists of phosphatized members of the group. Aso states that 11 out of 13 islands bear phosphate. Five of these islands, however, are listed under Chinese names that cannot be identified, or equated with the Chinese characters for the names of Woody and Rocky Islands as given by Chu.¹ In the case of one island the area given by Aso apparently permits identification.

The islands are evidently well vegetated. Woody Island is covered with trees; the others are covered mainly with bushes. Aso indicates that the phosphatization is contemporary, and some of the other available information seems to support this conten-

¹ My best thanks are due to Dr. Sydney C. Hsiao for help in this matter.

tion. It is, however, curious that the "Sailing directions" mentions a bird colony only on Triton Island, for which there appears to be no record of guano. There seems to be little detailed information available about the ornithology of these islands or the other islands of the China Sea. *Fregata m. minor* is, however, recorded from the Paracel group (Peters, 1931).

The islands are conveniently divided into an eastern Amphitrite group and a western Crescent group, with one outlying reef (North Reef), which apparently bears an emergent islet, north of the Crescent group, and another outlying island (Triton Island) southwest of the same group.

TREE ISLAND

LATITUDE 16° 59' N., LONGITUDE 112° 16' E.

The northern island of the Amphitrite group, a small islet with bushes and a single palm tree. The island is indicated in Aso's analytical tables as bearing nodular phosphate of the following composition:

N	CaO	P ₂ O ₅	(Al,Fe) ₂ O ₃
0.96%	48.26%	22.82%	0.79%

	POWDER	
N	2.23%	1.30%
CaO	—	—
P ₂ O ₅	16.48	30.35
(Al,Fe) ₂ O ₃	0.37	0.31

WOODY ISLAND

LATITUDE 16° 50' N., LONGITUDE 112° 20' E.

The largest island of the group, and, for this reason, To-shu Tao of Aso's list, based on a survey in 1922 by the Taiwan Government, may be identified with Woody Island. To-shu Tao is said to have an area of 1,746,000 m², of which 572,000 m² were covered by phosphate deposits. For Woody Island, Chu gives a much greater area for the deposit, namely, 1,291,600 m². The identification of the two islands, however, seems inevitable. Chu states that the material consisted mainly of powder, but that nodules from less than 1 pound to more than 40 pounds weight occurred. It appears from his general account

that the nodules are whitish, the powder brownish. His analyses of 16 samples indicates a very poor material containing:

	MEAN	
Moisture (100°–105°C.)	2.64–9.86%	5.20%
Total ash	59.26–89.12	69.89
P ₂ O ₅	1.24–16.26	10.88

Much of the ignition loss must be CO₂ from CaCO₃. Vegetable debris is said to constitute about 10% of the volume of the material.

Clerget gives the following analytical data for the surface layer (I), the subsurface layer (II), and the substratum (III):

	I	II	III
Moisture	11.15%	10.74%	2.53%
Ignition loss*	40.62	20.95	45.23
Total N	0.70	0.40	0
CaO	40.60	43.96	48.55
MgO	0.84	0.50	3.40
Al ₂ O ₃	tr.	tr.	tr.
Fe ₂ O ₃	0	0	0
P ₂ O ₅	14.52	30.97	0
CO ₂	17.38	3.42	40.65
SiO ₂	0.70	0.10	1.50

* This appears to include the moisture.

Chu indicated that the mean thickness was 25 cm. He concluded that the original reserve was 223,500 tons. Aso gives 243,028 tons estimated as present on To-shu Tao in 1922, corresponding perhaps to 40,000 tons P₂O₅.

Clerget's photograph of Woody Island shows trees growing over the deposit. Some of the twigs are perhaps whitened, but it seems improbable that phosphatization is now occurring, or was occurring at the time of the discovery of the island, as rapidly as at some time in the past. The profile given by Clerget seems to suggest the same conclusion. It is worth noting that there is no evidence of phosphatization of the substratum.

Aso gives the following partial analyses:

	NODULAR	
1.07%	—	—
44.64	—	—
30.60	24.01%	32.57%
0.11	0.18	0.26

ROCKY ISLAND

LATITUDE 16° 50' N., LONGITUDE 112° 21' E.

Said by Chu to bear brown powdery guano irregularly distributed over its surface, and in some places a little phosphate is incorporated into the shell breccia of which the island is composed. Aso gives an analysis of the powdery material:

N	CaO	P ₂ O ₅	(Al,Fe) ₂ O ₃
1.39%	38.81%	32.60%	0.49%

LINCOLN ISLAND

LATITUDE 16° 40' N., LONGITUDE 112° 44' E.

The eastern island of the Paracel group, about 2 kilometers long, with a maximum elevation of about 5 meters. It is covered with bushes and has a well in its center. Lincoln Island, according to Aso, has an area of 1,720,000 m², of which 756,000 m² are covered by phosphate. Clerget states that the material is poor and thin. He gives the following profile:

CENTI-
METERS

		P ₂ O ₅	P ₂ O ₅ SOL. IN 2% CITRIC ACID	CaCO ₃
0-20	Dark brown humic material, fine mineral matter impregnated with humic acid; containing fresh and dead organic matter, rolled coral of all sizes	17.85%	10.20%	34.40%
20-50	Calcareous brown soil with more or less rolled pebbles and coral branches; few roots	5.73	—	65.60
50-80	Yellow gravelly and pebbly soil, some vegetable debris, coral has scraped appearance	tr.	—	87.10
80-110	Very coarse whitish yellow sand with coral fragments and madrepores more or less transformed into water-worn pebbles	—	—	81.00
110-140	Gravelly yellow sand with coarse fragments of branched coral, little rolled, tubipores relatively common	—	—	88.90
140-170	White coral sand, coarse coral fragments very abundant, apparently a different species from above, a little white translucent coral, bleached coral, and tubipores	—	—	87.60

Aso gives for nodular phosphate from Lincoln Island:

N	CaO	P ₂ O ₅	(Al,Fe) ₂ O ₃
0.46%	52.77%	18.26%	3.11%

The total reserve in 1922 is given by Aso

as 320,834 tons. This can hardly have corresponded to more than 60,000 tons P₂O₅.

NORTH REEF

LATITUDE 17° 05' N., LONGITUDE 111° 26' E.

Presumably indicated as Île du Nord by Clerget as bearing an islet on which phosphate has been deposited, but no analyses or other details appear to exist.

PATTLE ISLAND

LATITUDE 16° 32' N., LONGITUDE 111° 32' E.

An island about 800 meters long and 9 meters high. It is covered with brushwood and mangroves 3 to 5 meters high and bears three tall palm trees. According to Aso the area of the island is 330,000 m², of which 105,000 m² are covered by phosphate. The powdery material contained:

N	CaO	P ₂ O ₅	(Al,Fe) ₂ O ₃
1.80%	39.53%	19.89%	0.09%

The reserve in 1922 was estimated as 52,019 tons, which would correspond to about 10,000 tons of P₂O₅.

ROBERT ISLAND

LATITUDE 16° 30' N., LONGITUDE 111° 30' E.

An island about 730 meters long and 8

meters high, covered with vegetation. According to Aso the area is 320,000 m², of which 164,000 m² are covered by phosphate.

Clerget gives two profiles, reproduced in condensed form below:

fragments. Some further migration downward into the coral sand has occurred, but in view of the evident porosity of the material it is remarkable that so little of the phosphate has been able to attack the lower strata.

CENTI-METERS	No. 1	P ₂ O ₅ TOTAL	P ₂ O ₅ SOL. IN 2% CITRIC ACID	CaCO ₃
0-20	Calcareous soil of plant origin, fine clear brown; many roots, both living and dead	32.63%	16.20%	7.80%
20-45	Similar but with soil aggregated in nodules, few roots	23.93	15.05	17.76
45-80	Very sandy soil, clear brown, traces of roots	14.30	—	32.20
80-115	Fine earthy agglomerated sand, clear chocolate colored, no large material, traces of roots	24.98	11.47	22.20
115-150	Shelly sand, rosy white, very fine, no roots	2.00	—	88.90
145-195	Yellow white sand with traces of rolled madreporarian coral pebbles	4.58	—	81.20
195-230	Very fine sand with madreporarian fragments of various sizes up to large blocks	3.80	—	76.40
230-270	Shell sand, yellowish pink, very fine with shell debris and coral branches, little water worn	3.64	—	80.00
270-340	Brilliant white sand with much coral debris, little water worn	3.29	—	70.00
No. 2				
0-60	Yellow concretionary soil with white yellow cement; black in places. In general, texture fine but with coral gravel and large fragments of oyster shells and traces of roots	17.85	8.92	46.70
0.60-110	Rolled coral breccia, some blocks poor in cement or cavernous	25.50	11.47	35.10
1.10-170	Fine-grained concretionary sand with shell debris (probably material <i>in situ</i> from side of old digging)	15.30	—	40.00
1.70-270	Concretional coral sand with much rolled coral debris (organic stain and roots probably secondary as material is apparently from edge of old digging)	9.55	—	75.00

The first profile is the more interesting, though there is no evidence that it is typical of the island. The second profile may be modified by secondary changes, as it was apparently taken from the side of an old digging. It will be observed that in the first profile no marked accumulation of phosphate has taken place below the level of the lowest root

Recent deposition may well be as great as that in the past, the maximum P₂O₅ content being at the surface.

Aso gives for powdery material:

N	CaO	P ₂ O ₅	(AL,FE) ₂ O ₃
1.20%	47.12%	37.53%	0.25%

He indicates that the reserve in 1922 was esti-

mated as 133,889 tons, which can hardly represent more than 33,000 tons P_2O_5 .

MONEY ISLAND

LATITUDE $16^{\circ} 27' N.$, LONGITUDE $111^{\circ} 34' E.$

An island about 1300 meters long and 6 meters high, covered with vegetation. According to Aso the island has an area of 407,000 m^2 , of which 144,000 m^2 were covered by phosphate. Chu merely states that guano is said to be found on the island. Aso gives an analysis of nodular material:

N	CaO	P_2O_5	$(Al, Fe)_2O_3$
0.50%	45.57%	32.89%	0.20%

The reserve in 1922 is given as 80,042 tons. Since the nodular material analyzed is probably richer in P_2O_5 than the average material, it is unlikely that more than 20,000 tons P_2O_5 were originally present.

DRUMMOND ISLAND

LATITUDE $16^{\circ} 28' N.$, LONGITUDE $111^{\circ} 45' E.$

An island about 800 meters long, said to be covered with brushwood and mangrove trees. According to Aso the island has an area of 228,000 m^2 , of which 64,000 m^2 were covered by phosphatic deposits. He gives an analysis of powdery material:

N	CaO	P_2O_5	$(Al, Fe)_2O_3$
1.90%	43.96%	27.87%	0.25%

The reserve in 1922 was estimated as 20,899 tons, indicating that about 5000 tons of P_2O_5 were present on the island.

DUNCAN ISLAND

LATITUDE $16^{\circ} 27' N.$, LONGITUDE $111^{\circ} 42' E.$

Lies with the next locality on a reef about 2 kilometers long. It is covered with bushes. According to Aso the island has an area of 344,000 m^2 , of which 72,300 m^2 were covered by phosphate; the reserve in 1922 was estimated at 30,639 tons.

Chu merely says that guano occurred in the interstices of the coral and shell of which the island was composed. No analyses were given by either author.

Palm Island, a small islet on the same reef as Duncan Island, has, according to Chu, a similar type of deposit. No analyses appear to exist.

Four estimates of area and mass of deposits on islands listed only under Chinese names are given by Aso, namely:

	TOTAL AREA	AREA OF DEPOSIT	MASS OF DEPOSIT
Shu Tao	2,410,000 m^2	950,000 m^2	31,960 tons
Po (Pe) Tao	3,600,000	30,000	1,290
Chung-Yang Tao	1,220,000	42,000	20,508
To-yen Tao	730,000	62,000	44 273

The two smaller islands are probably Palm and Tree, though the area of North Island given by Clerget is 100,000 m^2 and so about the same as the areas of these two. Po Tao, which Dr. Hsiao suspected to be North Island, seems too large to be equated with Clerget's North Island, the existence of which is not clearly indicated in the "Sailing directions" or on available charts. The identity of both the larger islands of this list therefore remains problematic.

The combined estimates for these four islands and for Duncan Island, for which there are no analyses, give 128,670 tons, which probably would correspond to 20,000 tons of P_2O_5 . Adding to this the estimates given above for individual islands, it appears that the total reserve for the group was about 210,000 tons of P_2O_5 or 90,000 tons P.

THE SHINAN ISLANDS

The Dangerous Ground is a large and little-known area of reefs lying in the eastern part of the south China Sea, westward of Palawan. The islands of this region constitute the Shinan group. A number of islands that lie along the western edge of the Dangerous Ground bore phosphatic guano. The central and eastern cays of the region are presumably wetter than these western islets and for this reason may lack guano deposits. It is, however, uncertain that they have been examined, as they are very inaccessible. It is to be noted that many of the islands on which guano occurs are said in the "Sailing directions for the western shores of the China Sea" to have wells from which fishermen obtain water. This suggests a higher rainfall than is usual on islands on which guano deposition is taking place. Tseng (1946) states that the mean annual temperature is $27.8^{\circ} C.$ The range of temperatures (? daily mean) is said

to be from 18.3° to 33.5° C., though occasionally temperatures up to 43° C. have been recorded. The wet season is from April to August. The torrential rainfall of Itu Aba is traditionally well known. It appears, however, from Aso's account that some of the deposits are modern ones and that their existence was first indicated by the congregation of sea birds on one of the islands, presumably Spratly Island. The islands listed as bearing guano by Aso and by Tseng are enumerated below, together with such notes on their general character as are available from the "Sailing directions" and from Tseng's brief but valuable account.

NORTH DANGER REEF

LATITUDE 11° 28' N., LONGITUDE 114° 20' E.

A reef with two sand cays, Northeast Cay and Southwest Cay; the position given is that of the former. Both cays are covered with bushes, and Northeast Cay has a conspicuous palm tree. Fishermen use a well on Southwest Cay. Tseng states that the Japanese started working phosphate on Southwest Cay in 1923, two years after they began on Itu Aba.

WEST YORK ISLAND

Apparently south of the North Danger Reef, mentioned as a phosphate island by Aso.

THI-TU ISLAND

LATITUDE 11° 03' N., LONGITUDE 114° 16' E.

On Thi-tu Reef, about 720 meters long, sandy, and with plantain and palm trees growing near a well, and mentioned by both Aso and Tseng as a phosphate island.

FLAT ISLAND

LATITUDE 10° 59' N., LONGITUDE 115° 48' E.

Mentioned by both Aso and Tseng as a phosphatic island.

LOAITA ISLAND

LATITUDE 10° 41' N., LONGITUDE 114° 25' E.

A sand cay about 270 meters long covered with bushes, and mentioned by Aso, but not by Tseng, as a phosphatic island.

ITU ABA ISLAND

LATITUDE 10° 23' N., LONGITUDE 114° 21' E.

The larger of two islands on Tizard Bank, about 1200 meters long and bearing small trees and bushes, with palms and plantains, near a well. This locality seems to have been the most important source of phosphate. Tseng indicates that the Japanese started work in 1921 and continued digging phosphate until 1929. The workings were evidently reopened in the late 1930's. In all, 67,000 tons were removed. The further working of phosphate on the island was forbidden by the governor of Formosa in April, 1939, because the operations had so modified the island that a large part of it was submerged by the sea. Itu Aba is said by Tseng to be the only inhabitable island of the group, and it was presumably believed to be of sufficient value to be worth preserving as such. This account coupled with the wetness of the island suggests an old deposit.

NAM YIT ISLAND

LATITUDE 10° 11' N., LONGITUDE 114° 21' E.

The smaller island on Tizard Bank, about 540 meters long, 180 meters wide, and 6 meters high. It is composed of sand and is covered with small trees and bushes, and is mentioned by Aso, but not by Tseng, as a phosphatic island.

SIN COWE ISLAND

LATITUDE 9° 40' N., LONGITUDE 114° 24' E.

Mentioned by Aso but not by Tseng as a phosphatic island.

SPRATLY OR STORM ISLAND

LATITUDE 8° 04' N., LONGITUDE 111° 45' E.

A flat island 450 meters long and 270 meters wide and about 2.4 meters high. It bears several conspicuous palms on its southwestern side. The "Sailing directions" state that during the breeding season sea birds build nests that look like bushes from a distance. The same source indicates that during June and July the eggs of sea birds cover the ground. Spratly is the only island indicated as having a bird colony, and the rather unsatisfactory information suggests that at least some species breed during or just before the rainy season.

AMBOINA CAY

LATITUDE 7° 51' N., LONGITUDE 112° 55' E.

About 140 meters long and 2.4 meters high. It is stated by both Aso and Tseng to have borne phosphate.

Aso gives the following partial analyses of guano and phosphates from these islands:

North Danger, Southwest Cay
Surface, powdery
Surface, lumps
Thi-tu Island
Lumps
Sandy, mixed with coral
Flat Island
Surface, powdered guano
Sandy, mixed with coral
Itu Aba Island
Surface, powdery
Surface, powdery
Spratly Island
Surface, powdery guano
Lumps
Sandy, mixed with coral

* Bauxite in Aso.

The phosphate is said to be highly soluble in ammonium citrate. The material is described by Aso as being porous and not easily dried, and of low specific gravity (presumably when dried).

The original reserves were estimated on the five islands of commercial importance by the Japanese company (Rasa Rock Phosphate Company) that worked the islands (I) and later by Aso (II), as follows, in tons:

	I	II
North Danger, Southwest Cay	262,000	50,000
Thi-tu	403,000	40,000
Flat Island	—	5,000
Itu Aba	146,000	60,000
Spratly Island	143,000	5,000
Total	954,000	160,000

The estimates of the company are certainly excessive. To Aso's total must be added 30,000 tons apparently removed from North Danger, Southwest Cay, and Itu Aba Island prior to his study in 1937, making an original total reserve of 190,000 tons. Aso's figure for

Itu Aba is certainly too low, since Tseng says 67,000 tons were removed from the island before work was prohibited in 1939. Aso's estimate would correspond to about 50,000 tons of P_2O_5 , while Tseng's estimate given as 250,000 tons for the whole group would correspond to about 66,000 tons P_2O_5 . An original reserve of 60,000 tons P_2O_5 or 14,000 tons P seems reasonable.

N	P_2O_5	$Al_2O_3^*$
1.99%	26.02%	0.50%
0.13	32.78	0.20
1.12	23.53	0.46
0.31	22.28	0.14
1.19	33.04	—
0.54	6.97	—
1.82	22.52	0.55
0.26	23.00	0.13
1.83	27.81	—
—	31.35	—
—	9.22	—

BATU KAPAL

LATITUDE 1° 33' N., LONGITUDE 125° 17' E.

A small island just north of Limbé Island off the northeastern end of Celebes. According to Hickson (1889) it is white with guano. He found no birds actually on the island in August, 1885, but he observed numerous boobies and frigate birds which he supposed roosted there at night. His illustration indicates a dome-shaped islet with a rugged irregular rocky surface. The locality is listed as a guano deposit by the Minenbureau (1928).

PULO MANUK

LATITUDE 5° 28' S., LONGITUDE 130° 20' E.

Said by Meise (1938), on the authority of a communication from H. Nevermann, to be a doubtful guano island.

MOROMAHU

LATITUDE 6° 08' S., LONGITUDE 124° 39' E.

The southeastern outlying islet of the Tukang Besi group, south of Celebes, said to bear guano (Minenbureau, 1928).

KAKABIA, KABIA, KAWI KAWYANG,
OR BAAR'S ISLAND

LATITUDE 6° 54' S., LONGITUDE 122° 13' E.

In the middle of the Flores Sea, described by the "East Indies pilot" (United States Hydrographic Office, 1924) as 38.1 meters high and entirely surrounded by a reef. Weber (1902) found the island to be composed of elevated reef rock. Both Weber and the "Pilot" state that the rocks and trees of the island are covered with guano, the former authority noting the presence of *Sula sula* (sub *piscatrix*), *S. leucogaster* (sub *fusca*), and *Fregata minor* (sub *Tachypetes ariel*). Wichmann states that Tromp (1880) recorded that some cargoes of guano from the island were shipped to England before 1879. Carl Ribbe (Schneider, 1895), however, found the guano to be inferior.

AMPALASA

LATITUDE 6° 56' S., LONGITUDE 121° 19' E.

ANCIENT PHOSPHATIZATION OF AN ELEVATED CORAL ISLAND

CHRISTMAS ISLAND

LATITUDE 10° 25' S., LONGITUDE 105° 42' E.

A remarkable, irregular island of greatest length about 19 kilometers, situated approximately 300 kilometers south of Java, from which it is separated by the Maclear Deep. Christmas Island in the Indian Ocean must be carefully distinguished from other islands of the same name; in the past some confusion has occurred in writings on phosphatic deposits.

Christmas Island is a very important source of phosphate. Sir John Murray, who first recognized the commercial possibilities of the deposit from a piece of phosphate rock collected by an exploring party from H.M.S. "Egeria" in 1887, realized that a thorough scientific study of the island should be made prior to its settlement. This study was undertaken by C. W. Andrews and resulted in the "Monograph of Christmas Island" (Andrews, 1900). The island is thus better known than are most of the important phosphate-bearing islands. It has had, however, a complex history, and in spite of Andrews' investiga-

SANGI SANGIANG OR SANGRANG

LATITUDE 7° 07' S., LONGITUDE 121° 28' E.

Two islets to the west of Kakabia, said to bear deposits (Minenbureau, 1928).

PULU BATU

A small islet off Pulu Seraya Ketjil, an island north of Toro Wado Ramba (latitude 80° 26' S., longitude 119° 52' E.) the north-western point of Flores, said by Pannekoek van Rheden (1913) to have borne about 100 m² of guano.

DATO ISLAND AND PASHIIRU ISLAND

The former 200 kilometers southeast, and the latter southwest, of Roti Island off the western end of Timor, said by Aso (1940) to be small coral islands frequented by sea birds and each bearing about 25,000 tons of guano and rock phosphate. The first of these localities may be identical with the Ashmore Shoals already considered (p. 271). The second has not been identified.

tion much remains to be learned about that history. From the standpoint of the present work, the major unsolved problems are of the same kind as are encountered in the study of the elevated phosphatic islands of the Pacific and relate primarily to the age of much altered limestones containing few if any recognizable fossils.

Christmas Island presents a curiously irregular outline, its coast being formed of five shallow bays separated by headlands. The center of the island is a gently sloping plateau rising from an altitude of about 150 meters on its southern margin to about 250 meters on the northern part of the island. Along the western, northern, and eastern edges of the plateau there is a series of hills rising to a maximum altitude of 357 meters. The phosphate deposits occur on the tops of some of these hills. The peripheral slopes of the island bear three series of inland cliffs. Though these cliffs are in part due to faulting, they represent in general the result of wave action. More than three stages in emergence are, however, recognizable, for two or three subsidiary old sea levels are represented by lines

of caves on the lowest inland cliffs or by raised reefs. Outside the lowest inland cliff the coastal terrace ends on its seaward margin in a modern cliff which is being extensively undercut. The modern fringing reef is little exposed at low tide.

The island lies on the northern edge of the zone of the southeast trade winds. From January to April, the wet season on the island, north winds bring heavy rains not infrequently. During the rest of the year the trade winds blow with little interruption. The whole of the island, save part of the coastal terrace, was originally covered with dense tropical forest. The soil mantle of the island is brown and extremely thick, in places over 13 meters deep, and presumably represents a lateritic residual soil formed by decomposition of the Tertiary volcanic rocks of the island. A number of endemic species of both animals and plants have been described. Andrews and his collaborators believed that a strong affinity with north Australia as well as with Java was exhibited by the biota. In the best-known group, the birds, it is probable that this Australian relationship was exaggerated. Most of the forms described as endemic species are now considered subspecies of species that are widely distributed in the East Indies. Andrews' observations suggest that although stray Javan birds and insects are continually carried to the islands by winds, the island was essentially saturated in its natural state and new colonists could not establish themselves. The breeding marine avifauna consists of *Anous stolidus* nesting on shelves on the sea cliffs, *Fregata andrewsi* Mathews breeding in trees nearer the coast, and *F. m. minor* more in the interior, *Sula leucogaster* mainly breeding on ground near sea cliffs, *S. sula rubripes* nesting in trees, *S. abbotti* breeding in tree tops usually on high ground, *Phaeton rubricauda westralis* Mathews, and the beautiful endemic orange *P. lepturus fulvus* Brandt.

The core of the island consists of Tertiary limestone and volcanic rocks. The uppermost of these is the Orbitoidal limestone, which Andrews considers to be of Miocene age. Most of the exposures of these Tertiary rocks are in cliff faces, and the central plateau is consequently less well known than the peripheral parts of the island. It seems probable,

however, that volcanic rocks and middle Tertiary limestones lie under the residual soil of parts of the central region. Raised reefs rest on the Tertiary rocks. The highest hills of the island are apparently composed of dolomitized limestone, so altered as to contain no recognizable fossils, except Foraminifera which appear to be of no stratigraphic significance. Nothing seems to be published as to the nature of the contact between these dolomitic rocks and the underlying strata. At an altitude of about 244 meters a limestone crowded with fragments of lithothamnium and *Halimeda* with a few Foraminifera, and another powdery chalky limestone containing hardened masses of Foraminifera were observed. These rocks are interpreted as lagoon deposits formed when the semicircle of high hills formed an atoll-like group of islands. The phosphate apparently forms irregular blocks up to 3 meters thick, lying on the dolomite. There are numerous groups of fantastic pinnacles on the central plateau and on the seaward margin of the hills, but there is nothing in Andrews' account to indicate that the phosphate fills cavities in a Karrenfeld. It would seem more likely that the major dissection of the surface of the island and the formation of the residual soil had taken place after phosphatization.

The main deposit occurs on Phosphate Hill. The material is described as very hard ($H=6-7$), of waxy luster and of a brownish white color. It is full of cracks and cavities, often lined with transparent phosphate which is beautifully banded. Sometimes fragments of dark and light phosphatic rock are bound together by a transparent yellowish phosphate deposited in concentric layers around the fragments.

A good deal of the rock is found lying about loose below the main deposit, and some has been incorporated in the raised reefs on the slope between Phosphate Hill and the sea. At many places on the plateau small black bodies, up to the size of a small pea, are found scattered about. They consist of an inner core of phosphate, a layer of manganese dioxide, and a thin outer coating of phosphate. The MnO_2 content of such bodies is about 18%. Andrews thinks that the manganese is derived from volcanic rocks, which

are supposed to have lain high enough to have been incorporated into the lagoon deposit.

The following two analyses (I by Ogston and Moore *in* Stutzer and Wetzel, 1932; II by Jacob, Hill, Marshall, and Reynolds, 1933) are available:

	I	II
CaO	52.39%	52.50%
MgO	1.68	0.10
Na ₂ O		0.53
K ₂ O		0.05
Al ₂ O ₃	0.82	0.80
Fe ₂ O ₃	0.43	
P ₂ O ₅	39.44	39.46
CO ₂	2.92	2.28
SO ₃	0.25	0.00
F	0.54	1.32
Cl	—	0.02
Combined H ₂ O, etc.	1.35	2.05

It is probable that only the fluorine determination of Jacob *et alia* should be regarded as valid. The same workers give a phosphate and a fluorine determination from a second sample, the two sets of determinations being:

P ₂ O ₅	F	F:P ₂ O ₅
39.46%	1.32%	0.0335
40.03	1.05	0.0262

These fluorine contents are lower than any given by the same authors for the elevated phosphatized coral islands of the Pacific, but are considerably higher than the four determinations that they gave for Curaçao phosphate. Jacob *et alia* also determined iodine in the sample used for the main analysis, finding 75.4 milligrams per kilo, a higher value than those obtained for Nauru or Ocean Island material, but lower than that of one of two Curaçao samples analyzed.

On Murray Hill, phosphatization of a volcanic rock, probably the tuff that lies just below the Orbitoidal limestone, has taken place, producing a deposit consisting of about 39% P₂O₅, 2.5% lime, 32.5% sesquioxides, 5% silica, and the remaining 21% mostly water (Andrews, 1900). This material is probably mainly (Al, Fe)PO₄·2H₂O. It consists of small brown spherules cemented together by a doubly refractive material.

A small amount of phosphate appears to occur on other hill tops on the eastern side of the island, notably on the western slopes of Gannet Hill.

According to the British Phosphate Commissioners the reserve in 1945 was 25,000,000 tons. Originally it must have been about 30,000,000 tons, corresponding to approximately 12,000,000 tons of P₂O₅.

GUANO ISLANDS IN THE WESTERN INDIAN OCEAN AND ADJACENT SEAS

PHOSPHATIC GUANO has accumulated on a number of islands in the western part of the Indian Ocean. These islands (fig. 70) may be grouped geographically in the following way:

Rodriguez in the Mascarene Islands, the Cargados Carajos, the Seychelles, Amirante and Aldabra Islands, and a number of other less important

localities off Madagascar

Islands along the east coast of Africa

Islands in the Red Sea

Islands on the southern coast of Arabia and within the Persian Gulf

This arrangement is somewhat arbitrary but proves convenient in practice.

RODRIGUEZ, CARGADOS CARAJOS, SEYCHELLES, AMIRANTE AND ALDABRA ISLANDS, AND MINOR MADAGASCAN LOCALITIES

The main islands to be considered have provided large quantities of phosphatic guano within the present century. Much of this material has been sold as Seychelles guano, but only two islands, Bird Island and Dennis Island in the Seychelles group, have actually yielded guano. The bulk of the Seychelles guano of commerce has been derived from the Cargados Carajos Atoll, the Amirante Islands, and from the Aldabra group off the northern end of Madagascar. A few other islands in the same region have had less important deposits.

There are considerable differences in the physiography of the various groups of islands. Bird and Dennis Islands, the Amirante Islands, with Alphonse Island which is on a separate bank, Providence Island and Cargados Carajos are low sand cays. Aldabra, Astove, Assumption, and St. Pierre Islands are elevated atolls formed of metamorphosed coral limestone; Farquhar Atoll and Cosmoledo are also of metamorphosed limestone but have been partly remodeled to produce land forms comparable to the sand cays (Vesey-Fitzgerald, 1941).

OCEANOGRAPHY

In the southern summer the equatorial current flows to the west between latitudes 10° and 15° S., impinging on the northern half of the east coast of Madagascar. To its north the Equatorial Counter Current is developed. There appears to be a considerable mass of water flowing north of the northern tip of Madagascar. Some of this water turns south along the coast of Africa, some flows north-east and joins the Equatorial Counter Cur-

rent. Conditions within the Mozambique Channel are evidently very complex. They have been summarized by Paesch (1926) whose maps indicate strong off-shore movement along the northwest coast of Madagascar from November to March, and very complex conditions in the vicinity of the Comoro Islands. In the region of greatest interest in the present work the movement appears to be uniformly westward from September to January. Local divergences appear in the vicinity of St. Pierre and Farquhar in the southern autumn, but there is no evidence of any local hydrographic disturbances likely to produce upwelling off Aldabra. Willimzik's (1929) maps indicate essentially the same water movements in the Channel as do those of Paesch, and the maps given by Schott and by Sverdrup, Johnson, and Fleming are in essential agreement on the general features of the circulation. During the monsoon season in the southern winter the northern Equatorial Counter Current disappears, and a well-marked transport of surface water from the region of the northern tip of Madagascar, up the coast of Africa, and northeastward across the southern part of the Arabian Sea takes place. At such a time, a small gyral apparently develops in the vicinity of the Seychelles. Schott indicates cold water upwelling off the northern tip of Madagascar, but without discussion.

It would appear from the account of Wheeler (1945) that the fisheries around the Cargados Carajos Atoll, or St. Brandan's Islands, are over five times as great as off Mauritius and Rodriguez to the south or the Seychelles to the north. Wheeler may well be

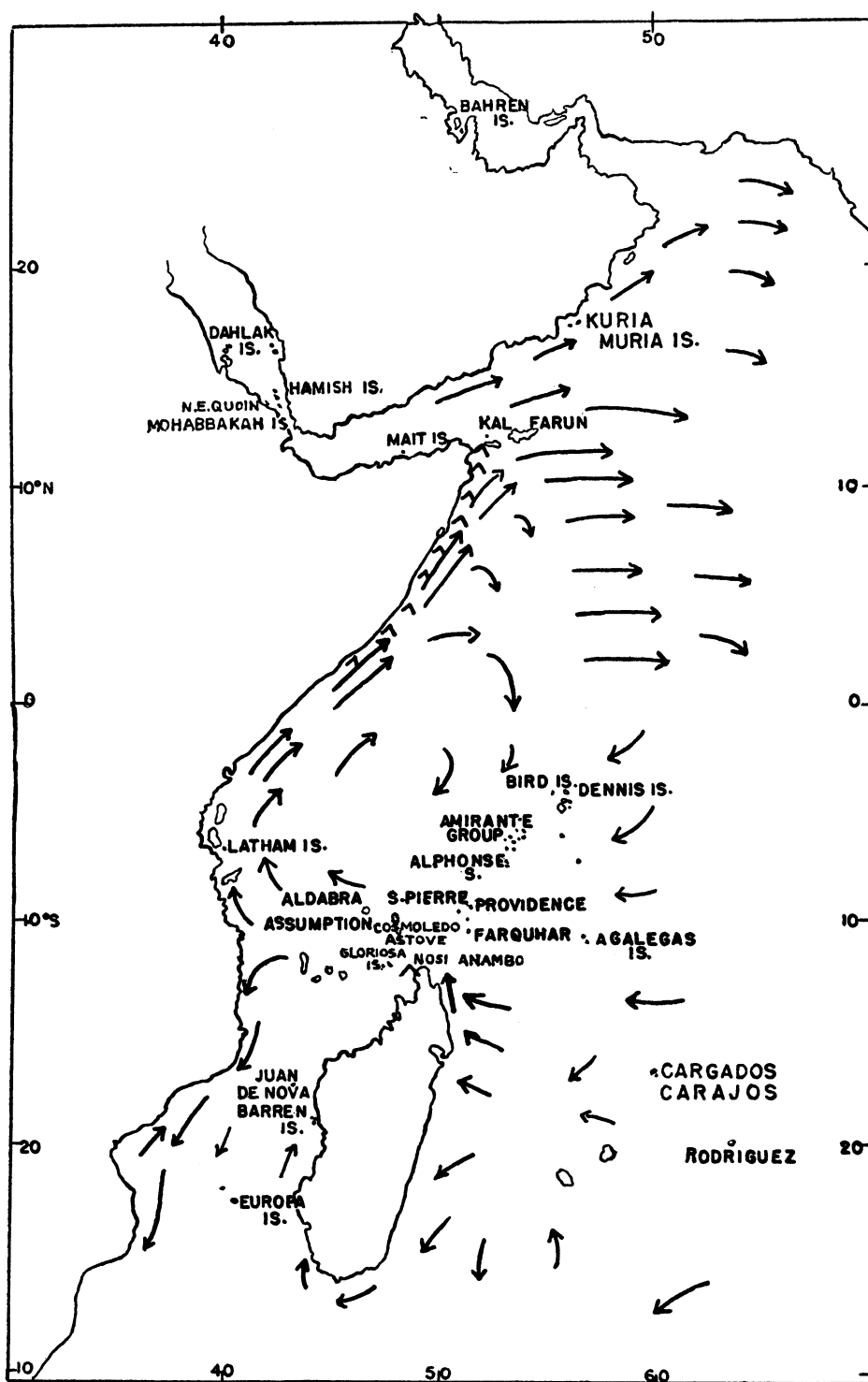


FIG. 70. Map of the western Indian Ocean to show position of the more important guano islands and general pattern of circulation during the southwest monsoon.

correct in supposing that this effect is in part due to the deposition of guano on the atoll, maintaining a high concentration of nutrient salts in its immediate vicinity; the increased productivity is, however, so great that the incidence of local upwelling would certainly seem probable. The maps given by Paesch (1926) give no indication of a divergence in the South Equatorial Current at any season in this vicinity, but it is doubtful if the information on which these maps are based is adequate to permit negative conclusions of any value.

CLIMATOLOGY

The data are, unfortunately, not extensive. The best account of the climate of Aldabra is given by Fryer (1911). The southeast trade winds blow strongly from May to October, during the dry season, when vegetation becomes parched, trees lose their leaves, and all life seems at a standstill. In November a calm, rainy season sets in. The temperature is higher than during the dry season, standing for long periods at about 38° C. with a relative humidity approaching saturation. Although Fryer says that the rainfall during the wet season is very heavy, Vesey-Fitzgerald gives the mean annual precipitation as but 380 mm. The other islands probably have a comparable climate. The "Atlas of climatic charts" (McDonald, 1938), however, suggests that the islands east of longitude 50° E., with the exception of Cargados Carajos, may experience steady rain in June to August and that passing showers may be experienced throughout the whole region during the entire year.

ORNITHOLOGY AND BIOGEOGRAPHY

On the sand cays the chief guano bird is undoubtedly the sooty tern or wideawake, *Sterna fuscata*¹ Linnaeus (= *fuliginosa* auctt.). On the only islands on which Fryer believed that significant guano formation is certainly still proceeding, namely, Bird Island in the Seychelles (Fryer, 1910) and Cargados Carajos (Gardiner and Forster Cooper, 1907), there are immense colonies of these birds.

Vesey-Fitzgerald indicates that the species

¹ The subspecific status of the birds of this region is apparently not adequately understood.

occurs on seven small islets of the Seychelles other than Bird Island, on African Banks, Remier Island, Desnoeufs Island, Étoile and Boudeuse Islands in the Amirantes, on Goelette Island in the Farquhar Atoll, and Wizard Island of the Cosmoledo Atoll. The last two localities, as has been indicated above, "have the configuration of sand cays due to secondary deposits" (Vesey-Fitzgerald, 1941, p. 525), though they are part of elevated metamorphosed atolls. The bird does not otherwise breed on the metamorphic limestone islands. Inadequate control of the exploitation of eggs has caused a great reduction in numbers on some islands. Desnoeufs Island had an estimated population of 5,000,000 pairs in 1931, but only 250,000 eggs were left to hatch in 1937. On Bird Island between 1933 and 1937 the estimated population was 65,000 pairs, though Fryer's earlier observation suggests that the colony was once much larger. On Goelette Island, Farquhar Atoll, 25,000 birds were reared after a heavy toll by egg collectors. The birds arrive at the islands at the time of the onset of the southeastern monsoon, usually late in May. Vesey-Fitzgerald gives evidence that dense colonies promote the welfare of the birds. Isolated breeding birds are shy and their eggs easily eaten by blue herons, turnstones, and crabs, while when closely packed the birds defend their nests vigorously. The large dense colonies destroy all the vegetation that has grown on last year's guano deposit. There is a story that they may sprinkle salt water on the plants, but Vesey-Fitzgerald never observed this. Isolated birds breeding among plants may be strangled in the trailing *Cassytha* vines. Once a colony is reduced artificially, its reproductive capacity per pair is evidently also reduced. There seems to be some sort of social stimulation of reproductive activity, but this may follow copulation rather than precede it. Normal breeding lasts from June to August, but egg exploitation delays the process and now most young birds cannot leave the breeding grounds until October. Many die at that time, as the monsoon has stopped blowing, sunstroke may intervene, or the exhausted parents may leave the breeding grounds.

In the colonies on Bird Island and Cargados Carajos, *Anous t. tenuirostris* (sub *A.*

leucocapillus, the white-headed noddy) nests in a zone of bushes and matted scrub around the main "fair" of *S. fuscata*, according to Gadow and Gardiner (1907), who write of the two species as the main guano birds of Cargados Carajos.

Anous stolidus pileatus, second only to the wideawake as a producer of edible eggs, is probably of much less importance as a guano bird. It is a very versatile nester and can occupy virtually every type of island. Individually it is stronger than *S. fuscata*, but colonies of the latter force the noddies into peripheral nesting sites where the two species meet, as on African Banks and Desnoeufs Island. Eggs are laid throughout the year, but the greater number of birds breed in July and August. Gadow and Gardiner indicate that *A. stolidus pileatus* and *A. t. tenuirostris* exclude each other from nesting territory, though they can occupy the same island, *A. s. pileatus* breeding on the ground, *A. t. tenuirostris* on trees.

Of the other terns *Sterna anaetheta antarctica* prefers small rocky coral islands, breeding throughout the year on all suitable islets in the region. Gadow and Gardiner note that this species and *S. fuscata* appear to be mutually exclusive, but do not indicate the underlying habitat preference indicated by Vesey-Fitzgerald. This preference doubtless reduces the importance of *S. anaetheta* as a guano bird, but it may contribute to deposits on islets in the Amirante Islands and on Providence. *Sterna sumatrana mathewsi* is found nesting in small groups above the high-tide mark on the Amirantes and Farquhar group. It is said by Gadow and Gardiner not to occur on islands where *Gygis alba monte* breeds. The latter species is much commoner in the Seychelles than the Amirantes and does not breed on the raised limestone islands. In view of the fact that it lays its egg on branches of trees, its distribution is doubtless largely determined by vegetation; it is unlikely that there is real competition with *S. sumatrana mathewsi*. The other terns breeding in the region are *S. bergii thalassina*, breeding on North Island, African Banks, and *S. dougallii arideensis*, found primarily on and around the rocky islands of the Seychelles proper and not known to breed on guano islands.

Two shearwaters, *Puffinus pacificus chlororhynchus* and *P. assimilis bailloni*, occur in the region, but only the former certainly breeds. It is abundant enough to provide large numbers of young birds for human consumption. It nests in holes under rocks on the rocky islands of the Seychelles and in burrows in the sand on the sand cays, being known on Bird, Marie Louise, Desnoeufs, and St. Joseph Islands.

It is very probable that part of the guano of the region was produced by boobies, though at the present time they are doubtless much less important than terns. The following notes are mainly from the admirable account of Vesey-Fitzgerald (1941). *Sula dactylatra melanops* breeds on Bird Island; on Desnoeufs, Étoile, and Boudeuse Islands in the Amirantes; on Goelette Island of the Farquhar Atoll; on West North, East North, Ployte, and South Island on the Cosmoledo Atoll, and on Assumption Island. The guano diggers on the last named have persecuted the birds so much that it is doubtful if young are reared. Both sand cays and islands of metamorphosed limestone are included in this list. The blue-faced booby spends the night on its breeding island throughout the year, and the day on its deep-water fishing grounds where squids and flying fish (*Exocoetus* sp.) are the chief food. The birds breed in September and October; only birds in adult plumage were observed incubating, in marked contrast to the Latham Island colony (p. 305). *Sula leucogaster* is said by Meinertzhagen (1930) to have a colony on Glorioso Island. Fryer speaks of great numbers on Aldabra, where it was molested by frigate birds, but Vesey-Fitzgerald found the brown booby uncommon throughout the region, noting a single nest on St. Joseph Atoll in the Amirante Islands. Fryer's record may be erroneous. The subspecific status of birds from this region is uncertain.

Sula abbotti Ridgway formerly bred in bushes on the large sand hill on Assumption. It is now most regrettably extinct, having been persecuted by guano diggers. The only other known breeding station is Christmas Island, Indian Ocean.

Sula sula sula breeds in a variety of bushes on the islands of metamorphic limestone. Colonies occur on South Island, Farquhar

Atoll, Menai, East North, Ployte, Wizard, and South Island, Cosmoledo Atoll, and on islets in the lagoon of Aldabra Island. There were formerly colonies on St. Pierre, Astove, and probably Assumption Islands. The birds spend the night on their breeding islands and are very gregarious. The trees that they occupy become "burnt," many twigs and branches dying (Vesey-Fitzgerald).

On St. Pierre, Gadow and Gardiner (1907) and Gardiner and Forster Cooper (1907) record the red-footed booby in immense numbers, forming guano. The birds were preparing to breed in low bushes in October, 1907. It seems improbable that guano deposited on bushes, particularly during or shortly before the rainy season, forms a stable accumulation, but the material collected from bushes, described below, is doubtless the product of this species. Gadow and Gardiner stated that the guano of Bird Island, Seychelles, was principally formed by *S. s. sula*. This is clearly erroneous, though Fryer (1910) writes that small colonies do breed on the island.

In view of the necessity of considering the history of these islands at a later stage of the discussion, some indication of the zoogeographical nature of their land fauna is desirable. The most striking character, historically if not at the present day, is the widespread presence of gigantic tortoises. These animals were so mercilessly pursued for food in the eighteenth century that they have now virtually disappeared. Moreover, they were transported from island to island, and as a result much hybridization apparently took place. Only owing to the excessive longevity of the animals has it been possible to gain any understanding of their systematics, for a few specimens of known history, caught in the eighteenth century, survived until the twentieth. The late Lord Rothschild, who devoted much of his learning and resources to elucidating the problem, has summarized the available information (1915). It appears that all the islands to be discussed below had populations of these animals, and all were related to subfossil Madagascan, rather than to Mascarene, forms. There is contemporary evidence that in the eighteenth century tortoises swam or drifted from one island to another of the Seychelles, so that their pres-

ence on small atolls such as Astove or Cosmoledo is not so extraordinary as might at first appear. The exact number of species or subspecies existing is uncertain. Rothschild recognized *Testudo elephantina* Duméril and Bibron from North Aldabra (Middle or Malabar Island), *T. daudinii* Duméril and Bibron from South Aldabra, *T. gigantea* Schweigger, supposedly from North-West or Picard Island, Aldabra, but more probably from the Seychelles, *T. sumieri* Sauzier from the Seychelles, *T. gouffei* Rothschild, probably from Farquhar Island, and the subfossil *T. grandidieri* Vaillant and *T. abrupta* Vaillant from Madagascar. There is no really certain evidence of habitat save in the case of *T. daudinii*, and the development of three subspecies, let alone species, on the very slightly separated Aldabra Islands is inherently improbable.

Though the main islands of the Seychelles have a slightly peculiar fauna and flora, the low coral islands to their southwest, with which the present account is mainly concerned, seem to show in the rest of their biota a low degree of insular endemism very similar to that apparently displayed by the tortoises. Thus of the dozen or more resident land birds of the Aldabra Atoll, almost all can be regarded as subspecifically differentiated, but they are closely related to Madagascan forms. The flora contains a few endemic elements, and the invertebrate fauna is likewise not devoid of peculiar species. The general biogeographical impression left by these islands is that there has been a continuous habitable land surface since the Pleistocene, but that there is no need to assume that the history of the terrestrial biota extends much further back in time.

DESCRIPTION OF THE ISLANDS

RODRIGUEZ ISLAND

LATITUDE 19° 43' S., LONGITUDE 63° 26' E.

The only one of the Mascarenes that has produced guano, a large volcanic island about 16 kilometers long. It is said by Lincoln (1939) that poor phosphatic guano is shipped from Rodriguez to Mauritius. This material presumably comes from outlying islets or cays on the fringing reef; nothing, however, is recorded of the occurrence. The

"South Indian Ocean pilot" (United States Hydrographic Office, 1927b) mentions a Booby Island, west of Mathurin Bay on the north side of the island. The two samples examined by Lincoln contained but 14.14% and 15.80% total P_2O_5 ; of this 47.4% and 48.2%, respectively, were soluble in neutral citrate and 87.8% and 85.8% in 2% HNO_3 . No phosphate dissolved in alkaline citrate.

CARGADOS CARAJOS OR ST. BRANDAN'S ISLES
LATITUDE $16^{\circ} 30' S.$, LONGITUDE $59^{\circ} 35' E.$

A group of islets, reefs, and shoals, few if any of which stand more than 3 meters above sea level. About a dozen islets are permanently emergent and have been named, but changes in topography continually occur. Gardiner and Forster Cooper (1907) indicate that Establishment Island, on the northern part of the reef, occupies but part of the site of one of two islands in this region 50 years previously. Coconuts and *Casuarina* trees are grown, but the natural vegetation appears to be scrub. Siren Island and the two Bird Islands, in the northern part of the group, are visited in August by immense numbers of breeding sea birds.

Gardiner and Forster Cooper (1907) have given the best account of these bird colonies. Each island is surrounded by a wave-raised ridge bounding a central flat area on which enormous colonies of *Sterna fuscata* breed, each bird hatching a single egg within a foot of its neighbor. Here and there clumps of *Erythroxylon* and *Tournefortia*, matted together with *Cassytha filiformis*, were pressed down by incubating *Anous tenuirostris tenuirostris*, while a few *Gygis alba monte* (sub *candida*) occupied the larger coral stones on the peripheral ridge. On Siren Island, where the bushes form a circle within the ridge, the three terns nest in concentrically arranged areas. On this island the interior, rather over a meter above the tide, was occupied by multitudes of *S. fuscata* chicks, while the breeding birds, apparently largely between these chicks and the bushes with *Anous*, were incubating a second laying. The substratum was coral and sand consolidated into a soft rock by the bird droppings and covered with soil composed of almost pure guano. Digging into the material, countless bones of young

and old birds were found and scarcely one chick in four appears to have survived. Vegetation is very stunted. A few *Scaevola* bushes, a single *Pisonia* tree, a rush, and five herbaceous species were observed. Many specimens of the plants were dead. Forty-two species of insects, a few jumping spiders, and myriapods were found, almost the whole fauna being scavengers or coprophagous. In addition to these three bird islands, Gardiner and Forster Cooper indicate that Pearl and Frigate Island on the western part of the bank, west of the main reef, have been dug for guano. The guano was first exploited by a company formed in 1900. The export soon rose to 1000 tons per year and from 1910 to at least 1922, 3000 to 4000 tons were annually obtained from the group. No detailed analysis has been published. The mean phosphate content is reported as 18% P_2O_5 (de Sornay, 1922), and as nitrogen was not considered in setting the price, it may be presumed to have been very low. A phosphate determination made on St. Brandan's guano more recently by Lincoln (1939) gave 30.96% total P_2O_5 , of which 20.8% was soluble in neutral ammonium citrate, none in alkaline citrate, and 54.0% in 2% HNO_3 . De Sornay specifically mentions Cargados Carajos, with Dennis Island, Assumption Island, and Aldabra Island, as the main sources of guano in the region. Wheeler (1945) indicates that St. Brandan's is still a source of guano; it is, however, not clear if this represents exploitation on the basis of the annual deposit.

Tempany (1928b) says that in certain of the Oil Islands, dependencies of Mauritius, an unknown amount of leached guano occurs. The name Oil Islands strictly refers to the Chagos Archipelago, but the St. Brandan's group is a dependency of Mauritius, and it is therefore not improbable that he is referring to this locality, the only dependency of Mauritius known to be regularly exploited. There is no mention of the Chagos Archipelago in Lincoln's table of phosphate contents of guano imported into Mauritius.

Tempany gives two analyses:

H_2O	7.18%	11.8%
N	2.85	0.6
P_2O_5	9.20	8.32
CaO	44.63	38.9
K_2O	tr.	0.0

There is obviously much admixture with calcium carbonate.

In 1856 Great Britain (Great Britain, Parliamentary Sessional Papers, Trade and Navigation, 1857-1867) received 442 tons of guano stated to have come from Mauritius. A further 493 tons were imported in 1858 and 1799 tons in 1866, making an aggregate of 2734 tons. The imports of 1866 realized £4.8.2 per ton, a price that indicates a moderately good phosphatic guano. It is difficult to know whether this material should be assigned to Mauritius itself, to early tentative exploitation of Cargados Carajos, or to some other source.

AGALEGA ISLANDS

LATITUDE 10° 26' S., LONGITUDE 56° 41' E.

Two low islands connected at low tide by a sandy ridge. The larger North Island is about 9.6 kilometers long and 3.2 wide and has a maximum elevation of 7.6 meters. The islands are largely given over to coconut cultivation (United States Hydrographic Office, 1927b).

Lincoln (1939) states that phosphatic guano is imported into Mauritius from these islands. He gives three phosphate determinations:

29.57% P_2O_5 , of which 28.9% is soluble in neutral citrate and 74.5% in 2% HNO_3

25.8% P_2O_5 , of which 27.6% is soluble in neutral citrate and 58.9% in 2% HNO_3

24.57% P_2O_5 , of which 23.3% is soluble in neutral citrate and 63.6% in 2% HNO_3

BIRD ISLAND

LATITUDE 3° 48' S., LONGITUDE 55° 18' E.

DENNIS ISLAND

LATITUDE 3° 48' S., LONGITUDE 55° 40' E.

The only islands on the Seychelles Bank known to have yielded guano, though the material from the Amirante Islands and Aldabra Islands passed commercially as Seychelles guano. Both islands are flat sand banks and contrast markedly to the other high granitic members of the Seychelles group. Both have been described in detail by Fryer (1910). Bird Island is a triangular island about 1650 meters long and 910 meters wide, protected on the eastern and southern coasts by a fringing reef. The ele-

vation of the island is uniformly about 4.3 meters. It is apparently entirely composed of calcareous sand, above which a layer of guano formerly existed. The sand has been phosphatized to give a surface stratum of soft friable brown rock, below which a white calcareous sand, in places cemented with phosphate, is found. A narrow zone of *Tournefortia argentea* and *Scaevola koenigii* encircled the island, and within this was a zone of the same species with tangled weeds, in places bound together by *Cassytha filiformis*. There are a few introduced coconuts and *Casuarina* trees and a few other cultivated plants. The entire center of the island, almost completely free of vegetation, was occupied by an enormous colony of *Sterna fuscata*. Fryer says that "it is quite impossible to give any idea of the countless thousands" of these birds. Outside the *S. fuscata* colony was a peripheral band of *Anous t. tenuirostris*, and a few small colonies of *Sula s. sula* and of a shearwater¹ were observed. The wideawakes arrive March 3, beginning to sleep regularly on the island about April 25. They start laying on May 18 and depart in September. In 1907, the year prior to Fryer's visit, no fewer than 909,000 eggs, probably nearly all of *Sterna fuscata*, were collected and sold in Mahe. Yet this inroad on the potential population did not at that time appear to affect the countless thousands that he observed. It is clear that the colony must have comprised hundreds of thousands, if not millions, of birds. In the 1930's, however, only about 65,000 pairs were nesting on Bird Island (Vesey-Fitzgerald, 1941).

Dennis Island, to the east of Bird Island, is slightly larger, but perhaps a little less elevated, the highest ground being 3.7 meters above low tide. The general structure and composition of the island are very similar, but the cementation of the sand below the phosphate has been carried less deeply. Fryer concluded that the vegetation was all secondary, the island having been once occupied by a bird colony. He attributes the disappearance of the colony to coconut cultivation to which almost the whole surface of the island is devoted. There was originally a pop-

¹ Vesey-Fitzgerald records *Puffinus pacificus chlororhynchus* and *P. assimilis bailloni* from the region but gives no nesting records for Bird Island.

ulation of giant tortoises on the island. The few that still exist are supposedly reintroduced. A single analysis of Dennis Island guano by Popp and Marxen is available and is given in table 26 with analyses from the next group of islands to be considered.

AMIRANTE ISLANDS

Most of the low coral islands (none over 6.1 meters above sea level) comprising this group, which lies on a separate bank just west of the Seychelles, appear to bear guano deposits. The "South Indian Ocean pilot" (United States Hydrographic Office, 1927b) mentions the two African Islands (latitude 4° 52' S., longitude 53° 09' E.), Eagle Island (latitude 5° 07' S., longitude 53° 19' E.), Marie Louise (latitude 6° 91' S., longitude 53° 09' E.) and the near-by Desnoeufs Island, Boudeuse Cay, and Étoile Cay near the Poivre Islands, as guano islands belonging to the Seychelles government. Alphonse Island (latitude 7° 01' S., longitude 52° 45'

E.) is privately owned. Desnoeufs Island, Boudeuse, and Étoile Cay are not permanently inhabited; the others all appear to bear coconut palms. The Alphonse guano is described (Anon., 1908) as consisting of lumps of a light chocolate brown color, containing white nodules evenly distributed through it, while that from Marie Louise is coarser, earthy in color, and with larger nodules. Gardiner and Forster Cooper, describing the shore of Poivre, note lines of rocks, of sand and coral formation, reddened by guano and partly recrystallized, which were once no doubt part of the island. Writing of Desroches Atoll, which is richly vegetated, they say that water is "well retained in these semi-guano lands."

The available analyses for known localities in the Seychelles and Amirante Islands are given in table 26.

The undetermined material in Popp and Marxen's analyses is doubtless largely carbonate. The distribution of the small quan-

TABLE 26

	Dennis (Popp and Marxen)	Marie Louise (Anon., 1908)	Alphonse (Anon., 1908)	Alphonse (Popp and Marxen)
Water	11.5 %	—	—	19.0 %
Total ash	74.7	—	—	57.9
CaO	38.6	46.90%	45.10%	30.7
MgO	0.3	—	—	0.2
Fe ₂ O ₃	—	0.08	0.17	—
Al ₂ O ₃	—	0.45	0.28	—
K ₂ O	0.07	—	—	0.03
CO ₂	—	5.54	4.61	—
Cl	0.08	—	—	0.13
P ₂ O ₅	27.70	30.84	29.26	20.72
Insol.	0.1	—	—	0.2
Ash constituents not determined	7.85	—	—	6.12
Oxalate	0.11	—	—	0.18
Total N	0.72	0.25	0.45	1.24
N · NH ₃	0.17	—	—	0.18
N · uric acid	0.35	—	—	0.77
N · purine	0.17	—	—	0.28
N · nitrate	0.15	—	—	0.0
N · keratin	0.05	—	—	0.02
Organic carbon	5.80	—	—	9.80
Organic carbon not accounted for	5.22	—	—	8.74
Organic matter directly determined	5.5	—	—	13.1
Organic compounds det. + 2 × org. C. not accounted for	12.1	—	—	20.5
Material not ash, NH ₃ or organic	8.1	—	—	9.8

tity of nitrogen is interesting. The retention of a considerable amount of uric acid, accounting for 37.6 % of the nitrogen in the Dennis and 61.6% in the Alphonse guano, is remarkable. The purine nitrogen determinations, 22.6% and 22.4% of the total nitrogen, respectively, are relatively very high. The decomposed Lobos de Tierra guano (p. 90), the only material with which these samples can be compared, agrees in the high proportion of the purines but has a low relative uric acid content. The organic carbon and organic matter determinations are obviously inconsistent, but presumably indicate that most of the organic matter consists of low nitrogen, high carbon humic material of plant origin.

FARQUHAR OR JOAO DE NOVA

LATITUDE 10° 13' S., LONGITUDE 51° 08' E.

An atoll bearing two large and several small islands formed of coral sand. The group apparently has yielded phosphatic guano, but this is stated by de Sornay (1922) not to be regularly exploited, though the best samples contain 31.5% P_2O_5 . Some aluminum phosphate is said to be present. The north island of the group is largely covered with planted coconuts, and the south island, as shown in the photograph given by Gardiner and Forster Cooper, is well vegetated. Goelette Island, on the southeastern side of the atoll, is said by Vesey-Fitzgerald to have a colony of *Sterna fuscata*; it is low, flat, and sandy, with few coconut trees, and is the most likely source of the guano.

ST. PIERRE

LATITUDE 9° 28' S., LONGITUDE 50° 55' E.

A small, roughly circular island apparently between 1.5 and 2 kilometers in diameter. It is separated from the Providence Reef to the west by deep water and appears to be a slightly elevated atoll. Gardiner and Forster Cooper give the maximum elevation above high tide as about 12 meters ("about 40 ft."). Vesey-Fitzgerald, however, indicates a lower altitude ("some 15 ft."). The shore is marked by low cliffs, and the center of the island is basin shaped. Raised reef rock is apparently present. When visited by Gardiner and Forster Cooper the whole interior was fringed with gnarled bushes of *Pemphis acidula* and the interior covered with small

trees, *Hibiscus*, *Pisonia*, and "tanghain." The other plants were said to be of "the regular species which can stand the guano. Of birds, the booby (*Sula piscator*) was breeding in every tree, an immense guano-forming colony." The vegetation is now largely destroyed by guano digging (Vesey-Fitzgerald, 1942). Gardiner and Forster Cooper say that much of the sand covering the coral rock is hardened and reddened by guano and humus. Some of this material is very rich in phosphate, and the soil above it consisted mainly of guano, presumably recent, and vegetable mold. The island was supposed to contain a quarter of a million tons of payable guano. The recent guano, as indicated above, is attributed by Gardiner and Forster Cooper to the immense colony of *Sula s. rubripes*.

ASTOVE

LATITUDE 10° 06' S., LONGITUDE 47° 45' E.

The easternmost of a group of islands somewhat west of the preceding and collectively referred to as the Aldabra group. Astove has been described in detail by Fryer (1911) and by Vesey-Fitzgerald (1942). It is an oval, raised atoll, apparently over 3.2 kilometers long. The land rim is complete save for a channel at the south end which dries at low water. The island is composed of coral rock with fossil corals *in situ*; both Fryer and Vesey-Fitzgerald were convinced that at present the lagoon is encroaching on the land surface. Much of the eastern part of the land rim is covered with sand dunes which reach an altitude of 13.7 meters, but there is some dissected rock surface with *Pemphis* scrub near the lagoon shore, like the champignon formation of Aldabra, to be described below. The western part of the land rim is covered with coral sand planted with coconuts, but at the northwest corner of the island where the land rim is widest there is apparently exposed coral rock that formerly bore guano, covering the surface and filling all the depressions and cavernous pits in the exposed limestone. Fryer says that little of the coral rock is metamorphosed, as it is on Aldabra, but that where metamorphosis has occurred there are phosphatic inclusions. During guano digging, bones, presumably of giant tortoises, have been found cemented into a rocky pinnacle.

COSMOLEDO

LATITUDE 9° 41' S., LONGITUDE 47° 31' E.

A large atoll of about 14.5 kilometers in maximum diameter. The exposed land surface is very small and extends over much less than half the circumference of the atoll. In all there are eight main and about four smaller islets; Wizard in the southeast and Menai in the southwest are the largest. The distribution of the small islets suggests that once a perfect land rim existed; erosion is still actively removing the land surface. The maximum elevation of the islands is about 3.3 meters. The best account of the atoll is by Fryer (1911) who states that the coral rock throughout is much metamorphosed and always contains varying amounts of phosphate. Platin rock, described below in the account of Aldabra, was not observed, and much of the surface of the larger islands is sandy. The two North-East Islands of the group have been greatly disturbed by the digging of phosphatic guano, and on West North-East Island there is phosphate rock, formed by the cementing together of sand and rubble by the action of phosphatic solutions, and containing fossil eggs of giant tortoises.

ASSUMPTION

LATITUDE 9° 56' S., LONGITUDE 46° 31' E.

Described as a slightly elevated coral island, crescentic in shape. Fryer says that dunes reaching a height of 27 meters occur in the southeast of the island, but the maximum elevation of the coral rock seems to be no more than 6.1 meters. Much metamorphosis of the coral has occurred, and in such metamorphosed rock phosphate inclusions are present. A "platin" rock, comparable to that described below, is also found, but is apparently due to denudation acting on coral *in situ*. The island was largely covered with thick scrub, though there were a few trees and bushes of *Pemphis acidula*. Ridges, pits, and crevices occur over the surface, initially due to irregularities of coral growth, but, once present, the pits tend to enlarge owing to the solvent action of rain water. Sea birds are said to have been numerous, but it is supposed that they were even more abundant prior to human occupation. The island was one of the two known breeding places of *Sula*

abbotti. Fryer states that the colonies of this species occupied the sand hills. In recent years it is clear that the bird colony has suffered badly, *Sula abbotti*, as well as the few native land birds, being extinct (Vesey-Fitzgerald, 1941).

The occurrence of guano on Assumption is described in an anonymous communication to the Imperial Institute (Anon., 1911). About 100 tons per acre of surface guano were present, and the material was still accumulating. Fryer states that along the east coast guano formed a covering 15 cm. thick. The older beds of surface guano appeared to be richer in phosphate than the newer material in which much calcareous sand is present. The most valuable material, however, was that concentrated into the pits by the action of water. Fryer records a species of *Dracoena* (? *D. reflexa*) as growing in such places. This pit guano was consistently higher in phosphate than the surface guano, though only 106,000 tons were believed to be present against 270,000 tons of the surface guano. It is supposed that in the old beds descending solutions had converted the admixed calcium carbonate into phosphate. The analyses given are not detailed.

	PIT GUANO (AFTER RAIN)	SURFACE GUANO (OLD)	SURFACE GUANO (NEW)
$\text{Ca}_3\text{P}_2\text{O}_8$	61.04%	72.83%	8.49%
H_2O	19.57	8.70	10.00
$(\text{Al}, \text{Fe})_2\text{O}_3$	3.67	0.60	0.50
CaCO_3	—	1.20	60.00

These data indicate that between 33,000 and 120,000 tons of P_2O_5 were originally present on the island. A more recent analysis (Lincoln, 1939) indicates 28.20% P_2O_5 , of which 36.1% is soluble in neutral ammonium citrate but none in alkaline citrate.

ALDABRA

LATITUDE 9° 24' S., LONGITUDE 46° 22' E.

A large atoll about 32 kilometers long in its long east-west axis (fig. 71). There are four main islands separated by narrow channels; of these islands South or Main occupies the entire southern half of the land rim, and is virtually as long as the atoll. Several small islets exist in the lagoon; of these Esprit at

the western end is of some importance in the present study. The width of the mainland rim varies from about 400 meters up to 8 kilometers. The land rim is surrounded by a fringing reef; cliffs rise about 4.5 meters high, bounding the seaward coasts of the islands. The cliff exposures show corals *in situ*. Over the greater part of the interior of the island the coral has, however, been metamorphosed, producing a partly crystalline limestone,

the champignon rock, and there is always some phosphatic material in the latter, apparent, in freshly broken surfaces, as brown patches on a white ground of carbonate. Fryer thought that the metamorphosis of the coral was in some way connected with the presence of the phosphate.

On Esprit Island there is a ridge of a curious conglomerate, yellow at the top, almost black lower down; this rock projects along the

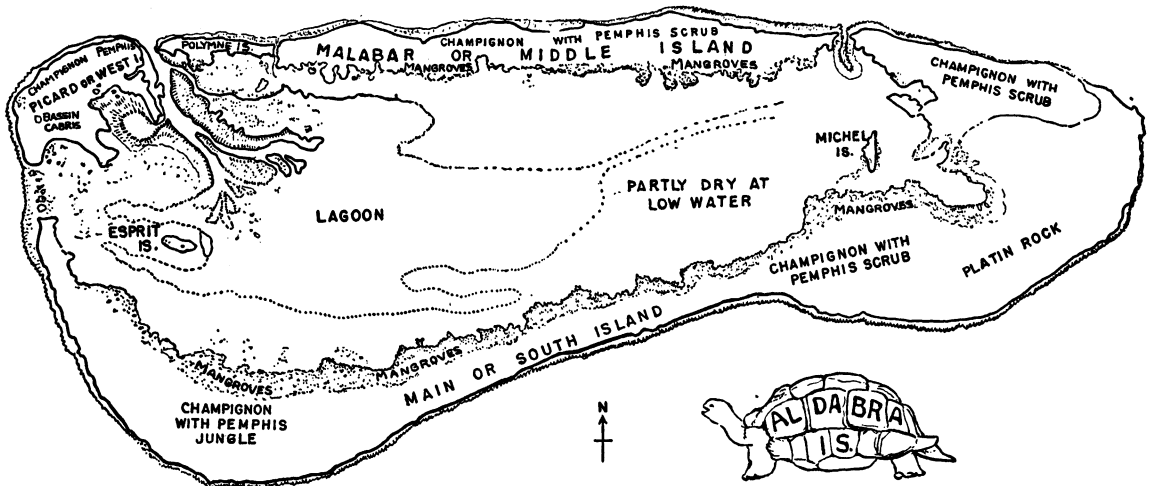


FIG. 71. Map of Aldabra Island.

containing phosphatic inclusions. This material is greatly dissected into sharp points, projecting pinnacles, and deep pits, which may be filled with salt tidal water. There is little soil on this Karrenfeld; the main vegetation is a dense scrub of *Pemphis acidula*, a plant whose roots penetrate the crannies in the dissected, metamorphosed coral rock. The large areas of such dissected rock, covered with *Pemphis* scrub, are known locally as champignon. There seem to be no analyses available and no indication whether the champignon is dolomitized.

In the eastern part of the island a different type of surface is found locally. It is composed of relatively unaltered coral fragments, fragmentary lithothamnium, and molluscan and echinoderm fossils with pockets of Foraminifera. Fryer concludes that this deposit represents lagoon debris. This detrital rock weathers to form flat, pavement-like surfaces, locally called "platin." The guano of Aldabra apparently filled numerous pits in

shore as large, wind-polished boulders. At the top of the ridge a material superficially like flint occurred; at the sides there are pinnacles up to 3 meters high with molluscan fossils. The shell rock was found in one place to penetrate the conglomerate. The latter and the flint-like rock are both calcium phosphate.

On Picard Island, part of the northern land rim, a cavity partly filled with salt water about 3 meters deep was found in the platin rock. Round the sides of the basin phosphate rock like that on Esprit was found, with a conglomerate of *Carcharias*, *Diodon*, and *Scarus* teeth and bones of giant tortoises, cemented together with phosphate. Fryer concludes that the marine fossils were washed into a cavity in the coral limestone by the sea, and that later, after elevation, guano was washed in also by the rain. The rocks observed were formed from these materials. This occurrence on Picard Island is probably identical with the record (Anon., 1908) of considerable phosphatization of coral rock on

the eastern side of the Bassin de la Plaine des Cabris. The phosphatized rock is described as reddish or yellow and is said to have contained 37.1% P_2O_5 . On Esprit Fryer supposes that a cavern was also originally present and that denudation had removed most of the surrounding limestone after the cavity had become full of phosphatized material, leaving only the phosphate ridge. This explanation demands that the minimum elevation on the site of Esprit Island was at the time of maximum guano production at least as great as the present maximum elevation of about 9 meters. This presumably implies a complete land rim with no openings into the atoll, which may well have been dry. The flint-like rock is evidently a collophanite comparable to the nauruite of Nauru and indicates that material at the top of Esprit Island was formed in a basin.

Fryer's interpretation of the history of Aldabra is essentially in terms of elevation and then continuous dissection and solution by rain water, a process which finally permitted the sea to break through channels in the land rim to refill the shallow lagoon. Early in the process, soon after elevation, vast numbers of birds must have colonized the island, covering much of its surface with guano. Fryer believed that in recent times the bird populations of all the islands of the region under discussion, save Bird Island in the Seychelles and Cargados Carajos, have suffered reduction. He considers that this occurred prior to human settlement, as he believes that there were no records of other modern bird islands comparable to the two localities just mentioned. He points out that on Bird Island there is no evidence that vegetation can compete successfully with the birds, unless human interference occurs. Fryer suggests the great colonies that produced the phosphate on Aldabra, Assumption, Astove, and the other islands consisted of transient populations, driven south by the glaciation in the north. None of the species involved is likely to have been seriously inconvenienced by glaciation, being more or less tropicopolitan. There is, moreover, no reason why descendants of these birds should all have returned to the north; if they could have continued to breed on the Aldabra Islands, some of their descendants surely would have done so.

Comparison of Aldabra with Nauru, Ocean, and Makatea Islands is of interest and will be considered later.

GLORIOSO ISLAND

LATITUDE $11^{\circ} 34' S.$, LONGITUDE $47^{\circ} 13' E.$

Two small islands, Île Glorieuse and Île du Lise, with various rocks, are situated on a reef south of the preceding locality. The larger island, Île Glorieuse, is just under 2 kilometers long. Both islands are of coral rock and bear trees. Guano is worked here according to the "South Indian Ocean pilot" (United States Hydrographic Office, 1927b), and the locality is entered on Holzschneider's map. There is said to be a colony of *Sula leucogaster* (? *plotus*) on Glorioso Island (Meinertzhagen, 1930).

NOSI ANAMBO OR WOODY ISLAND

LATITUDE $12^{\circ} 16' S.$, LONGITUDE $48^{\circ} 39' E.$

One of several islands off William Pitt or Andramahiba Bay, on the western shore of the northern tip of Madagascar. It is described in the "South Indian Ocean pilot" as a "strip of sand surrounded by a reef on which is a row of casuarinas." Duclos (1928) states that, at the time of his writing, the island supposedly contained 40,000 metric tons of phosphatic guano containing 15% to 25% P_2O_5 , but that much had been removed. An original reserve of at least 50,000 tons seems probable.

JUAN (JOÃO) DE NOVA OR ST. CHRISTOPHER ISLAND

LATITUDE $17^{\circ} 03' S.$, LONGITUDE $42^{\circ} 46' E.$

A low sandy island in the narrowest part of the Mozambique Channel. It is about $5\frac{1}{2}$ kilometers long and up to 2 kilometers broad; apparently the interior of the island is low, about 1 meter above high tide mark, but is surrounded by higher dunes reaching an altitude of 15 meters (Voeltzkow, 1897). There is apparently elevated reef rock *in situ* on the island, though it is largely covered with coral detritus and sand. According to Voeltzkow (1897), who gives the best general account of Juan de Nova, the island was formerly well wooded but has been largely cleared. Voeltzkow noted very few birds in June, 1895. The "South Indian Ocean pilot," however, indicates that thousands of eggs

can be obtained in the breeding season. From Paesch's (1926) maps it is legitimate to conclude that hydrographic conditions are very complex in this vicinity.

Lacroix (1918) has described phosphatic guano occurring in depressions between the dunes in the northern part of the island. The material consisted of a brown pulverulent substance, tobacco brown in color. Below it the coral sand and rock have been phosphatized to a depth of a few decimeters, the brown phosphate passing gradually into carbonate. Isolated pieces of limestone embedded in the powdery guano may be completely phosphatized. Phosphatization of the calcareous material takes place with virtually no morphological change, a yellow layer of colloidal phosphate replacing the carbonate. Sand grains are usually mammillated after phosphatization, and the interstitial spaces remain open between them. Some of the larger pieces of fully phosphatized material are rolled and covered with a thin white layer of alteration. The nature of this is not indicated, but its presence shows that though the process of phosphatization is probably not very ancient, it is not of contemporary occurrence.

Analyses (Orcel, 1918) have been made of both the powdery guano and the underlying phosphatized material.

	PHOSPHATIC GUANO	UNDERLYING PHOSPHATE MINERAL
H ₂ O at -110°C.	5.32%	4.00%
H ₂ O at +110°C.	10.08	7.97
Organic		1.27
CO ₂		0.14
Cl	0.14	0.29
F	—	undetectable
SO ₃	0.58	0.56
P ₂ O ₅	35.19	35.56
CaO	46.85	48.63
SrO		0.17
MgO	tr.	1.75
Al ₂ O ₃	0.38	0.15
Fe ₂ O ₃	—	undetectable
Insol.	0.03	0.05

The analysis of the phosphatized coral rock is remarkable in that, although virtually no carbonate is present and but small amounts of other anions, there is a great excess of CaO. Allowing for all the other substances present, the corrected molecular CaO:P₂O₅ ratio is 1:0.264. The complete absence of iron

and of fluorine is interesting, as is the determination of strontium, though this is unlikely to be particularly accurate. A sample analyzed by Jacob, Hill, Marshall, and Reynolds, however, contained 32.29% P₂O₅ and 1.68% F, the F:P₂O₅ ratio thus being 0.0520. Duclos says that the range of phosphate contents is from 28.68% to 37.84%, while the nitrogen content is given as 0.25%. He indicates a reserve of 100,000 metric tons; 70,000 tons have been removed from this island and Nosi Anambo. Since Juan de Nova is the more important phosphate island, an initial reserve of about 150,000 tons seems probable.

THE BARREN ISLANDS

A group of small, low, sandy islands 10 to 20 kilometers from the western coast of Madagascar. According to Duclos, three of these islands contain guano, namely:

Nosi Maroantaly (latitude 18° 25' S., longitude 43° 54' E.) with *ca.* 500 tons of mediocre material containing 13.54% P₂O₅

Nosi Andrano (latitude 18° 32' S., longitude 43° 53' E.) with *ca.* 200 tons of poor material containing 8.09% P₂O₅

Nosi Lava¹ (latitude 18° 35' S., longitude 43° 56' E.), with *ca.* 1000 tons of mediocre material

Nosi Andrano is said by the "South Indian Ocean pilot" (United States Hydrographic Office, 1927b) to be wooded. The vegetation of the other two islands consists mainly of bushes. The deposits are obviously of no great importance.

ISLANDS OFF THE SOUTHERN WEST COAST OF MADAGASCAR

Duclos lists a number of small islands off the southern part of the west coast of Madagascar.

NOSI TROZONA

LATITUDE 21° 45' S., LONGITUDE 43° 13' E.

A rock off the Nosi Lava on the Tsingilo-

¹ The identity of this island with the Nosi Lava in the Barren Islands is not certain. Two other islands of the name lie off the Madagascan coast, one farther north, the other farther south. The entry in Duclos' table suggests either the Barren Island or the Nosi Lava off Nosi Trozona, the next locality listed. His map, however, gives the Nosi Lava in the Barren Islands and that farther north, but not the southern one. It is reasonable therefore to conclude that the locality in the Barren Islands is implied.

filo Reef, perhaps the most important of these, having an estimated reserve of about 260 tons of mediocre guano. The other islands listed below are said to have a supposed aggregate reserve of 100 tons:

Nosi Andriangosy (= Andriangori of the "Pilot" and charts; latitude 20° 50' S., longitude 43° 46' E.)

Nosi Andrianmitariko (latitude 21° 06' S., longitude 43° 42' E.)

Nosi Andromona (latitude 21° 40' S., longitude 43° 22' E.)

Nosi Ratafani (latitude 21° 50' S., longitude 43° 16' E.)

Nosi Bemoka (latitude 22° 00' S., longitude 43° 15' E.)

Nosi Andrahombava (latitude 22° 02' S., longitude 43° 12' E.)

Nosi Fasi (latitude 22° 04' S., longitude 43° 11' E.)

Nosi Hao (latitude 22° 06' S., longitude 43° 09' E.)

EUROPA ISLAND

LATITUDE 22° 21' S., LONGITUDE 40° 20' E.

An island 8 kilometers long and nearly 5 kilometers wide in the Mozambique Channel. The "South Indian Ocean pilot" gives its maximum altitude as 24.4 meters and says that it is composed chiefly of sand and has a vegetation cover mainly consisting of bushes and rushy grasses, with large *Casuarina* trees at the northeastern end. According to Duclos the island bore 5000 tons of a poor phosphatic guano containing 5% to 7% P_2O_5 , a determination by Lacroix of 4.97% P_2O_5 being specifically quoted.

OTHER MADAGASCAN OCCURRENCES

In addition to localities just described Duclos mentions Nosi Bory with a supposed reserve of 250 tons of leached guano and Nosi Very-very with a reserve of 600 tons of leached guano. It has not been possible to ascertain the positions of these islands.

SEYCHELLES GUANO FROM UNSPECIFIED LOCALITIES

Apart from the accounts available for individual localities some descriptions and

analyses of "Seychelles guano" from unspecified localities (Anon., 1908; Voss *in* Stutzer, 1911; and de Sornay, 1922) have been published. According to de Sornay hard, coherent fragments in the guano are often richer in phosphate than the more pulvulent material; de Sornay uses the term *platin* for such material. While Fryer uses *platin* for a flat, calcareous surface which may be covered by guano, Stanley Gardiner (1931) who had great experience in the Indian Ocean, indicates in his admirable book on coral islands that "*platin*" is the term given to a hard guano surface. It is probable that the highly phosphatic fragments described by de Sornay represent in part a crust guano comparable to that found in the Pacific.

Four analyses of material from unspecified localities by de Sornay indicate 0.47%, 0.84%, 0.85%, and 1.20% N; he states that 0.5% to 0.8% is the ordinary range of variation. In some places, however, a typical fresh nitrogenous guano can be obtained in small amounts by removing the dried excreta of birds from the branches of shrubs. Such material, presumably derived from *Sula sula*, contains:

H ₂ O	10.60%
Organic	48.20
Total N	12.90
N·NH ₃	3.00
N·organic	9.00
CaO	19.06
MgO	1.10
K ₂ O	1.05
Na ₂ O	2.10
P ₂ O ₅	16.20
SO ₃	1.69

De Sornay also indicates that in four phosphatic samples, Fe_2O_3 varied from 0.18% to 0.72% and Al_2O_3 from 1.72% to 4.06%; these are distinctly higher values than occur in the Pacific and are reminiscent of some of the Caribbean phosphatic guanos. The presence of the sesquioxides has been attributed to floating pumice (Dupont, 1925). Two phosphate determinations by Lincoln (1939) give:

30.80% total P_2O_5 , of which 41.5% is soluble in neutral ammonium citrate and 63.3% is soluble in 2% HNO_3

32.00% total P_2O_5 , of which 17.7% is soluble in neutral ammonium citrate and 46.2% is soluble in 2% HNO_3

These probably refer to Bird, Dennis, or one of the Amirante Islands.

TOTAL QUANTITY OF GUANO

Dupont (1925, 1928) estimated that during the 25 years prior to 1914, 200,000 tons were exported from the islands belonging to the British Empire, and that a like quantity remained containing 60% $\text{Ca}_3\text{P}_2\text{O}_8$. This corresponds to about 110,000 tons P_2O_5 . There was also about a million tons of low-grade material available for local use. This would presumably contain at least a mean amount of 30% $\text{Ca}_3\text{P}_2\text{O}_8$, corresponding to about 140,000 tons P_2O_5 . The total deposit would thus be equivalent to about 250,000 tons P_2O_5 .

For the Madagascan deposits, Duclos (1928) estimates that 70,000 tons had been removed from Juan de Nova and Nosi Anambo. The former is a larger and richer deposit, and a mean value of 25% P_2O_5 for the mixed material would seem reasonable. The total removal would thus be 17,500 tons P_2O_5 . There were estimated to be 100,000 tons left on the first-named island. Some would doubtless not contain as much as the 28% P_2O_5 given in the analyses, so that an estimate of 25,000 tons P_2O_5 is reasonable. On Nosi Anambo 40,000 tons were supposed to remain containing 15% to 25% P_2O_5 , so that an estimate of 8000 tons is reasonable. Europa Island had 5000 tons containing 5% to 7% P_2O_5 , and so would contribute about 300 tons. The other localities had about 3050 tons of avian guano, little of which was rich, and so they may probably be allowed but 300 tons P_2O_5 . The aggregate estimate is thus:

Juan de Nova and Nosi	
Anambo	17,500 tons removed
Juan de Nova	25,000 tons remaining
Nosi Anambo	8,000 tons remaining
Europa	3,300 tons remaining
Other islets	300 tons remaining
54,100 tons P_2O_5	

The entire southwestern region of the Indian Ocean thus seems to have contained about 300,000 tons of P_2O_5 on its islands prior to exploitation. In view of the fact that high-grade material was still being received in Mauritius in 1938 and that islands such as Agalega supplied some of this, though they

were not regarded as phosphatic islands when Dupont wrote, it is probable that this estimate is conservative.

CHRONOLOGICAL ASPECTS OF THE GUANO DEPOSITS ON THE ISLANDS OF THE WESTERN INDIAN OCEAN

None of the deposits on the sand cays, namely, Bird Island, Dennis Island, the Amirante group and Alphonse Island, Providence Island and Cargados Carajos, can be of any great age, and the same must be true of the islands such as Goelette in the Farquhar Atoll and Wizard in the Cosmoledo Atoll which appear to be remodeled islets of metamorphosed reef covered with sand. The guano on Bird Island and Cargados Carajos is certainly due to the existing bird colonies, and though the bird populations may have been reduced on some of the other islands and entirely exterminated on others such as Dennis, the sand cays of this region give no evidence in favor of separating modern from ancient post-Pleistocene phosphatization. The deposit on Juan de Nova within the Mozambique Channel may, however, be referable to a somewhat more remote period than those on the sandy islands northeast of Madagascar. The small deposits on the coastal islands of Madagascar are presumably quite modern but are inadequately known.

The islands composed of elevated metamorphosed reef rock appear to present a different problem. On St. Pierre the major guano production may have antedated the development of the rich vegetation that formerly covered the island, but it seems to have accumulated largely after coral sand had covered the reef rock. Astove is composed of coral rock that is little metamorphosed; most of the phosphate which had accumulated lay on this unaltered coral, but where the latter was metamorphosed phosphatic inclusions occurred. Cosmoledo and Assumption are more metamorphosed than is Astove, and phosphatic inclusions occur throughout the altered reef rock. Most of the phosphate on Astove seems derived from the phosphatization of coral sand and rubble. On Assumption the older phosphate is richer than the more modern sandier material. On all of these islands it seems reasonable to suppose that at some past, but not necessarily

very remote, time larger bird colonies existed than were recorded in historic times, and that some of the guano solution percolating through porous metamorphosed reef rock has produced phosphatic inclusions. Without knowing something of the chemical nature of the metamorphism of the reef limestones it is hardly possible to pass judgement on Fryer's belief that the formation of phosphatic inclusions is related to the metamorphism. The hypothesis here suggested may on further study prove much too simple. Most of the guano must either have phosphatized sand or have been leached of its soluble contents and left as phosphatic guano at the surface. Fryer's testimony that only on a few islands, such as Bird Island and the islets of the Cargados Carajos group, are the existing colonies large enough to account for the deposits is of great value in indicating a decline in guano production in the region, even though his explanation of the decline is not acceptable.

The phosphatic deposits on Aldabra appear to be more complex. Here the structure of Esprit Island described by Fryer indicates that a very considerable amount of denudation has taken place since the first phosphatization of the atoll.

Much of the surface of the island is apparently covered with champignon or Karrenfeld, with little or no filling between the pinnacles. The whole account of the island suggests what might have happened to one of the elevated Pacific phosphate islands if dissection had continued until the present day, while phosphatization occurred much less intensely than it must have done on Nauru or Ocean Island. It is obviously impossible to form any idea of the chronology of the Aldabra deposits. The guano described as filling pits in the champignon may well be no more ancient than that on Assumption or the other islands of the region. The phosphate of Esprit Island, which originally lay in cracks and caves in the atoll surface, at least 9 meters above sea level but now appears as elevated rock from round which the limestone has been largely lost, must be of considerable antiquity. The account of Esprit is in some ways reminiscent of Ajawi, where it appears that elevated pinnacles of phosphate project above the general level of the island. A thorough modern study of the fossil mollusks of Aldabra and the adjacent islands might provide valuable results.

ISLANDS ALONG THE EAST COAST OF AFRICA

Three localities only are known to have yielded guano, namely, Latham Island off Dar-es-Salaam, Kal Farun between Socotra and Cape Guardafui, and Mait Island or Bur-da-Rebschi off the Somaliland coast in the Gulf of Aden. That more localities producing guano are not known is probably owing to the lack of islands, particularly along the stretch of coast between the Equator and latitude 10° N., a region that would otherwise seem to be especially suitable for the occurrences of deposits. A little east African guano is recorded as having been imported into Great Britain in the middle of the last century. Forty-eight tons were received in 1846, 1 ton in 1849, and 1363 tons in 1852. The nature and source of this material are problematic (Great Britain, Parliamentary Sessional Papers, 1854).

CLIMATOLOGY

The southern part of the coast under con-

sideration has a high, markedly seasonal rainfall, a mean precipitation of 1025 mm. per annum being recorded at Dar-es-Salaam and 1518 mm. per annum at Zanzibar. Most of this rain falls between November and May, the wet season culminating in April. Proceeding northward up the coast the rainfall declines, though the seasonal distribution is maintained until, within the Gulf of Aden, but 63 mm. per annum are recorded at Berbera (United States Hydrographic Office, 1936a, 1943). The mean temperatures are, of course, high throughout the region, ranging from about 26° C. in the southern part to about 30° C. in the northern part. The mean monthly relative humidity at 7 A.M. is high (85%–93%) at Dar-es-Salaam throughout the year; at 2 P.M. lower values are obtained, and there is a strong seasonal trend, the mean monthly minimum of 61% occurring in June. At Berbera the mean relative humidity is 65%, with values of 47% to 49%, lower than

those recorded during the rest of the year, in June, July, and August. The data on the breeding periods of birds at the three guano localities are inadequate to permit interpretation of the effect of the climate on the deposition. It is probable that the Latham Island deposit has formed under rather damper conditions than usually occur on tropical phosphatized islands. It is possibly significant that the main guano bird here is *Sula dactylatra melanops*, which perennially remains near or on the island and is a race of a species that has a particularly good reputation as a guano producer in the West Indies. It is not difficult to imagine that with more intermittent guano production all the material deposited might be washed away.

OCEANOGRAPHY

As the three localities are so far apart it is not remarkable that their oceanographic as well as their climatic characters are rather different. During the southern summer the main water movement along the coast is southward, the North Equatorial Current impinging on the African coast and turning south to about latitude 5° S. During the southern winter, when the southwest monsoon starts to blow, there is a very marked northward movement of water, the Somali Current, along and away from the African coast, with much upwelling off the Somaliland seaboard. The major upwelling occurs north of Latham Island, but that locality lies within the section of the coast in which reversal of the current system occurs (Möller, 1929), and greater vertical mixing is likely here than would be expected if the current due to the southwest monsoon was not developed.

The hydrography of the Gulf of Aden is more complicated; the published sections are mainly longitudinal and relate to the central part of the channel. Matthews (1926) shows that a tongue of low-salinity water, derived from the northward-flowing monsoon current, usually extends across the mouth of the Gulf during the northern summer season. This water may be difficult to distinguish from the results of local upwelling. There is, however, evidence of upwelling in the vicinity of Socotra, and Dr. E. F. Thompson indicates verbally that the Sir John Murray expedition found upwelling along the Somaliland coast

of the Gulf. Kal Farun and Mait Island therefore are certainly in regions of considerable vertical mixing, while Latham Island is probably in such a region. It is not unlikely that the main limitation to the existence of phosphatic guano islands along the east African coast is a lack of suitable islands between the Equator and Cape Guardafui, in the region in which upwelling at the time of the southwest monsoon is best developed.

ORNITHOLOGY

The available information relating to the southern part of the region has been admirably summarized by Moreau (1940), while the birds of the Somaliland coast have been discussed by von Heuglin (1873), by Archer and Godman (1937), and by North (1946). There is a lack of detailed information on the ornithology of the middle station, off Abd-el-Kuri. Since only one guano island is known in the section of the coast discussed by Moreau and one off Somaliland, the detailed accounts of the birds are given below, and no general summary is attempted. It is, however, worth noting that North (1946) concludes that throughout the coast from Somaliland to Tanganyika Territory the breeding season is the time of the kharif and southwest monsoon, in other words, the time of upwelling in the region of the Somali Current.

DESCRIPTION OF THE ISLANDS

LATHAM ISLAND OR KIZIMKARI REEF

LATITUDE 6° 54' S., LONGITUDE 39° 36' E.

This island lies 28 miles (50 kilometers) from the coast of Africa and 11 miles south-east of Zanzibar and has an altitude of 3 meters (10 feet) above spring high tide. The island has been described by Owen (1833), by Ingrams (19—?) in an undated, printed sheet seen by Moreau (1940), and by G. F. Cole in Moreau (1940). Owen gives the dimensions as 320 meters (350 yards) by 165 meters (180 yards), but it is possible that the island is being removed by wave action or, as Moreau supposes, by local subsidence, for Cole gives 183 meters (600 feet) by 76 meters (250 feet), a large discrepancy hardly likely to be due to errors on the part of experienced naval officers. The surface is flat; Cole thinks

that irregularities may have been worn down by the treading of myriads of sea birds.

The island is apparently regarded as a haunt of devils (Ingrams *in* Moreau); this belief, coupled with its remoteness, may have protected its bird colony. Owen noted the great number of birds, recording that some "were of the sooty pettrel kind, but by far the greater number resembled the gannet," though a diversity of coloration in the latter was noted. Moreau indicates how the booby population was variously misinterpreted by east African ornithologists and shows that it apparently consists entirely of *S. dactylatra melanops*, of which species about one-third of the individuals breed in immature plumage. It appears that the boobies remain throughout the year on and around the island, usually within a radius of 16 kilometers. They seem unknown at Dar-es-Salaam, 50 kilometers away, though the species has once been recorded from Zanzibar, 120 kilometers from Latham Island (Pakenham, 1943). Owen's "sooty pettrel," as Moreau supposes, must be *Sterna fuscata*.

The terrace-like interior of Latham Island forms a slimy white plateau covered with about 30 cm. of guano (Anon., 1920). The presence of this material was noted in 1824 by Owen (1833) and later by Cole (*in* Moreau, 1940). Analysis (Anon., 1920) indicates a typical phosphatic guano.

H ₂ O	15.24%
Organic matter	1.88
Total N	0.76
Nitrate N	0.31
Ammonia N	0.012
CaO	35.36
K ₂ O	0.33
P ₂ O ₅	29.52 (19.10 "available")

Lumps of calcium phosphate and of calcium carbonate, sand, and plant remains are said to be mixed with the guano.

KAL FARUN

LATITUDE 12° 25' N., LONGITUDE 52° 10' E.

Two steep, rocky islets (maximum altitude 282 feet) off Abd-el-Kuri, between Socotra and the mainland, used as a source of guano by the Arabs in the last century (Guillais, 1856). The abundant birds and resulting deposit are mentioned in the "Sailing direc-

tions for the Red Sea and Gulf of Aden" (United States Hydrographic Office, 1943), but no analysis exists. The region is known to be inhabited by some race of *Sula leucogaster* (Archer and Godman, 1937).

MAIT ISLAND OR BUR-DA-REBSCHI

LATITUDE 11° 20' N., LONGITUDE 47° 38' E.

East of Berbera, a rocky island 130 meters high. Water is said to collect in pools at the summit and to percolate through the rock (United States Hydrographic Office, 1943). The island was visited by von Heuglin, November 13–15, 1857, by Archer, February 1, 1919 (Archer and Godman, 1937), and by North, November 21–22, 1942 (North, 1946). The first-named observer found enormous numbers of birds, the most abundant being the Red Sea noddy, *Anous stolidus plumbeigularis* Sharpe. The colony was so great that there appeared not to be sufficient room to accommodate the whole population at one time. The Red Sea sooty tern, *Sterna fuscata somalensis* Heuglin, and a few tropic birds, *Phaeton indicus* Hume, and masked boobies, *Sula dactylatra melanops* Heuglin, were also present. When Archer visited the locality it was virtually deserted except by the last-named species. North found about 240 *S. d. melanops*, and a fair number of *A. s. plumbeigularis*, but the sooty terns had already bred and left at the time of his visit. Von Heuglin states that the guano, mixed with sand, dead birds, and eggshells, is washed by the winter rain into cracks in the rock. The material exploited by the Somalis and Arabs must therefore be a phosphatic guano. North says the island looks white and that the granite gneiss of which the island is formed is exposed only on vertical rock faces. Archer and Godman indicate that the name Bur-da-Rebschi is a Somali pun meaning either "guano-mound" or "hill-of-trouble." Numerous fights have occurred here to gain possession of the guano, the monopoly to which was often granted by rival Somali factions to different dhow-masters and dealers in Aden. Farquharson (1928) indicates that the disputes became so acrimonious that exploitation ceased, at least for a time. The material was taken to the Hadramaut to fertilize tobacco. In recent years peace

has been enforced, and 400,000 to 600,000 pounds of guano are collected annually. It is believed to be harder to obtain than formerly, apparently because the bird colony has been somewhat reduced by rats.

The only chemical account of the guano is that of Farquharson (1928) who, however, was unable to land on the island. He says the superior guano formed a white crust on the island, while inferior material, reserved by the Somalis for anyone not Somali or white, filled cracks in the rock. A typical sample, from the Berbera customs house, contained:

Feathers, bone, etc., 0.8%
Retained by 1/8-inch sieve, 25%, containing 14.90% P_2O_5
Retained by 1/20-inch sieve, 17.5%, containing 16.06% P_2O_5
Passing 1/20-inch sieve, 56.7%, containing 56.7% P_2O_5

Fragments of granite, aplite, flint, black slate, and hornblende gneiss occurred in the material. Lumps free from such minerals were picked out and gave the following analysis:

P_2O_5	18.6%
CaO	1.2
MgO	tr.
Al_2O_3	5.4
Fe_2O_3	6.2
SiO_2	49.4
Indet.	19.0

If it be assumed that the iron and aluminum are combined with phosphate as barrandite, $(Al,Fe)PO_4 \cdot 2H_2O$, 13.0% P_2O_5 would be accounted for, and 6.7% combined water would be included in the undetermined material, part of which is presumably organic. The recorded calcium, even if it were all present as monetite, $CaHPO_4$, which is most improbable, would account for only 1.5% P_2O_5 , and unless very soluble salts were present the only other possible phosphate would be of magnesium, which is present in traces only. It is conceivable but improbable that an aluminum phosphate more acid than $AlPO_4$ might be present in the material. The occurrence of an immense amount of silica, supposedly as flint or quartz, is, moreover, unlikely in phosphatic alteration of igneous rocks on a tropical island, and if the silica partly represents aluminum and iron silicate minerals, from the underlying rock, the excess of P_2O_5 over bases becomes quite impossible. It seems that this analysis must represent in part phosphatization of the underlying rock, the phosphatic material perhaps being mixed with relatively fresh guano. It seems equally certain that there are analytical or typographic errors in deriving or presenting it, and that the bulk of the considerable annual yield of the island has a composition more closely approaching that of other guanos from tropical islands with seasonal precipitation.

ISLANDS IN THE RED SEA

CLIMATOLOGY

The guano islands of the Red Sea all lie in the southernmost part, off the Eritrean coast. The region is dry, but not so dry as is the northern part of the Red Sea where rain virtually never falls. During the period of the southwest monsoon, from May to September, the prevalent winds in both northern and southern sections are north-northwest, but in the southern section a reversal in wind direction takes place, so that southerly winds prevail between October and April. Such rain as occurs falls during this winter season. The mean annual precipitation seems somewhat greater on the Egyptian than on the Arabian coast. The following stations are close to the islands to be con-

sidered (United States Hydrographic Office, 1943):

Massawa (latitude $15^\circ 37' N.$, longitude $39^\circ 27' E.$), 185 mm. per year
Kamaran Island (latitude $15^\circ 20' N.$, longitude $42^\circ 36' E.$), 74 mm. per year
Perim (latitude $12^\circ 39' N.$, longitude $43^\circ 26' E.$), 66 mm. per year

OCEANOGRAPHY

Thompson (1939) has pointed out that seasonal change in the prevalent winds should lead to seasonal reversals of circulation in the southern Red Sea. During the monsoon period a southward-flowing current would be expected along the west coast and a movement of water from east to west, causing

upwelling along the eastern shore. During the northern winter these movements are reversed south of about latitude 22° N., so that the whole southern water mass tends to rotate, upwelling occurring along the western shore and at the southern end. A powerful surface current also enters the south end at this season and possibly produces anti-cyclonic eddies. The theoretical expectations are in general confirmed by the data available. The region of the guano islands thus seems to be liable to considerable vertical exchange, with phosphate being brought periodically into the trophogenic zone. Dr. Hamed Abdel Fattah Gohar kindly informs me that the bird population and general productivity are greater at the southern end than at the northern end of the Red Sea.

DESCRIPTION OF THE ISLANDS

A vague reference to Red Sea guano (Anon., 1869) and Brehm's (1870) statement that colonies of boobies, terns, and gulls breeding on bare rocky islands deposit considerable amounts of guano probably both refer to the localities listed below. The following analyses of Egyptian guano by Voelcker (1864):

H ₂ O	17.19%	15.06%
Org. and NH ₄ salts	39.50	39.30
Total N	11.81	10.93
Earthy phosphates	18.28	19.29
CaSO ₄	2.76	3.15
Alk. salts, largely NaCl	20.93	20.39
Sand	1.34	2.21

may also refer to localities in the Red Sea; indeed any other provenance appears unlikely. The individual localities that are known to have yielded guano are situated in two groups of islands, the Dahlak Archipelago off Massawa, and the Hanish Islands and Mohabbakah Islands on the sill forming the southern hydrographic boundary of the Red Sea. One locality, Scheel Reef, mentioned by Martelli (1902), has not been identified.

DAHLAK ARCHIPELAGO

Islets demarcating the Massawa Channel, off Norah Island, are stated to be the source of ashy white guano containing bird and fish remains and diatoms, analyzed by Ampola (1901). More specifically, reefs near Isratu

Island and Vusta, or Wusta, Island, a coral island about 2.4 kilometers long and 21.5 meters high, are mentioned by Martelli (1902) as being guano islands. Analyses are given below.

NORTHEAST QUOIN OR FANAADIR ISLAND

LATITUDE $13^{\circ} 45\frac{1}{2}'$ N., LONGITUDE $42^{\circ} 10'$ E.

In the Bay of Barassoli, one of three white rocky islets; it rises to a height of 45 meters and is said to be frequented by many sea birds. A layer of guano 1 to 2 cm. thick covered the rock.

LITTLE HANISH ISLAND

LATITUDE $13^{\circ} 53'$ N., LONGITUDE $42^{\circ} 49'$ E.

Lies east of the preceding, nearer the Arabian than the Eritrean coast. A bank runs northeast from it and bears small islets, the highest of which reaches 25 meters in height. The gray guano, greatly contaminated with sand, analyzed by Martelli, appears to have come from such islets.

ISOLOTTI MOHABBAKAH

Four small islets, stated to be "more or less covered with bird droppings, which gives them a whitish appearance" (United States Hydrographic Office, 1943). Flat Island (latitude $13^{\circ} 24'$ N., longitude $42^{\circ} 33'$ E.), the second from the north, is said to have an elevation of about 12 meters and to have a flat white surface. Farther south Harbi (latitude $13^{\circ} 22'$ N., longitude $42^{\circ} 49'$ E.) is 25 meters high, and Sayal (latitude $13^{\circ} 20'$ N., longitude $42^{\circ} 34'$ E.), 15 meters high and rocky. Guano samples from the last two islets were analyzed by Martelli.

In addition to the analyses given in table 27 Martelli examined three earlier samples from unspecified Eritrean localities, finding 7.46% to 8.51% N. The most interesting feature of these analyses is the presence of nitrogenous guanos, notably on Northeast Quoin Island, on the reefs off Little Hanish Island when the analysis is put on a sand-free basis (5.43% N), and on the islets from which Ampola's material was obtained. No great thickness of guano is apparently found on any islet, the 3 to 4 cm. recorded on Scheel Reef being the greatest. It is quite likely that

TABLE 27

	Islets off Norah I., Massawa Channel (Ampola)	Reefs off Isratu I.	Vusta I.	N.E. Quoin I.	Reefs off I. Hanish	Harbi I.	Sayal I.	Scheel Reef
H ₂ O at 100° C.	6.84	7.090	18.140	11.820	7.002	17.550	13.800	9.732
Organic	28.45	20.691	13.828	52.766	13.965	20.042	12.104	19.250
Total N	8.61	3.514	1.819	15.029	2.954	0.784	1.344	2.779
N · NH ₃	0.514	0.805	0.266	1.379	0.658	0.525	0.228	0.784
Uric acid	13.11	n.d.	n.d.	present	n.d.	n.d.	n.d.	n.d.
K ₂ O	1.48	0.694	0.224	1.781	0.505	0.452	0.784	0.859
Na ₂ O	1.57	1.207	3.051	2.601	0.960	2.580	7.204	1.008
CaO	31.54	30.500	27.480	10.155	12.160	15.560	10.840	28.560
MgO	1.20	1.887	2.210	1.234	1.290	10.132	5.472	2.031
(Al,Fe) ₂ O ₃	tr.	3.995	2.130	1.225	4.820	0.240	6.850	4.290
SO ₃	2.54	2.318	2.077	1.478	0.918	6.860	5.471	1.977
P ₂ O ₅ total	5.38	11.840	25.990	12.192	11.706	20.102	15.616	28.083
Sol. in H ₂ O	n.d.	0.269	0.448	1.414	0.646	0.122	tr.	0.288
Sol. in citrate	n.d.	6.598	19.936	10.477	8.684	10.022	9.824	15.213
CO ₂	19.59	15.996	1.162	tr.	0.099	2.356	tr.	1.199
Cl	1.41	1.142	3.428	2.673	1.061	1.664	8.434	0.265
Sand, loss	tr.	2.640	0.28	2.075	45.514	2.462	13.425	2.746

all the material is quite recent and that most of the islets are probably morphologically unsuitable for accumulation. The presence

of nitrogenous guano on the eastern side of a continent is, however, exceptional and of some interest.

ISLANDS ON THE SOUTHERN COAST OF ARABIA AND WITHIN THE PERSIAN GULF

KURIA MURIA OR KHORYA MORYA ISLANDS

A group of five islands off the south coast of Arabia, the westernmost, Haski Island, lying at latitude 17° 28' N., longitude 55° 37' E. The islands are composed mainly of igneous rocks, and the central one, Jezirat Hallanyia, rises to a peak of 500 meters. The surface of the islands is for the most part barren. In the "Sailing directions," Haski Island is said to be white with guano. Von Heuglin indicates that the noddy is one of the most abundant of the sea birds frequenting the group; Haines indicates "gannets" on the eastern island, Jezirat Kabliya. Baker (1929) says that Ticehurst believes that *S. dactylatra* inhabits Haski. As is indicated below, Freemantle was impressed by the general lack of sea birds in September, 1854.

In the middle of the nineteenth century the Kuria Muria Islands attracted the attention of the guano trade. A deposit was supposedly discovered by a Capt. Jno. Ord,

and was examined by a Capt. Stephen G. Freemantle, who arranged for the cession of the islands from the Imaum of Mosul to the British Crown. Captain Freemantle's report on the deposits was hardly encouraging, and other warnings as to their nature were also published (Haines, 1857). Freemantle (Great Britain, Parliamentary Sessional Papers, 1857) found no recent guano on the island of Haski and noted few birds there. At the north end of the island, in narrow water courses, there was a general diffusion of inferior, and apparently old, guano. This had a mean depth of about 60 cm.; 40% to 60% of the material consisted of sand and stones. On two level spaces deposits about 46 cm. deep were noted. Such material contained 30% stones, and the total mass present was not more than 3000 tons. At the south end of the island a different kind of guano is said to have been encountered, forming a considerable deposit, estimated as about 40,000 tons

but containing 50% insoluble matter.

On Jezirat Kabliya (Jibleea), Freemantle found dispersed patches of guano on all the plains of the island, but "no bonâ fide mass of the real stuff." He estimated the reserve on this island as 76,000 tons, of which half was stones and other refuse. The best deposits were in five caves, but they aggregated only 230 tons. As on Haski, birds appeared to be absent, and there was no vestige of modern guano. Markham (1862), however, states, probably not from personal observation, that the whole island was coated with a white, polished, slippery layer, of which the aggregated mass was estimated to be 500,000 tons. He also indicates that rain had washed phosphate from this layer which had been redeposited as a stalactite layer on the rock below the guano. A small rock called Cshurzoud, northeast of Jezirat Hallanyia, ap-

from Haines' accounts and from the "Sailing directions" that at least Haski and Jezirat Kabliya had deposits, but the assembled sea captains complained that the statement that three islands were covered with guano was "decidedly an incorrect statement" (Anon., 1858).

The analyses of Anderson (1859), Nesbit (1860), and Voelcker (1860) indicate the material to have been a phosphatic guano much contaminated by sand and in some cases containing appreciable amounts of $(\text{Al,Fe})\text{PO}_4$. Nesbit's analyses are the most complete; the mean and extreme values are given below. Owing to the lack of separation of iron and aluminum it is impossible to determine the exact phosphate content. The ranges for three analyses of hand-picked samples of material from the Haski deposit, collected by Freemantle, are also given.

	NESBIT		FREEMANTLE
		Mean	
H ₂ O	2.48-12.25%	6.97%	6.50-10.00%
Org.	5.66-14.42	9.02	10.00-12.00
SiO ₂	7.55-47.30	32.43	18.00-40.00
(Al,Fe) ₂ O ₃	0.0*-6.90	2.45	—
(Al,Fe)PO ₄	0.0*-15.29	5.85	—
Ca ₃ P ₂ O ₈	11.92-63.85	27.74	26.00-46.00
P ₂ O ₅	0.0-1.66	0.19	—
Alkaline salts	0.0-15.91	5.25	11.50-34.00
CaSO ₄ ·2H ₂ O, etc.	0.0-22.95	10.11	—

* No samples lack iron and aluminum; reference to oxide or phosphate is doubtless arbitrary, but phosphate must have been present in some.

peared to bear a little guano in cavities on its surface.

In spite of the unfavorable nature of Freemantle's report, Ord was not discouraged, and with partners formed a company which took out a lease and evidently issued a prospectus. A fleet of guano ships set out, but the venture was hardly a success. On January 14, 1858, a meeting of the captains of the vessels that had arrived at the islands was held on board the ship "J.K.L." and a document drawn up protesting against the inaccuracies in the circular issued by Ord, Hindson, and Hays, the company formed to lease the rights to the guano. From this statement it appears that some guano had been obtained, but the work had been hampered by rain, lack of labor, and the difficulties of loading. It is clear from Freemantle's and

Voelcker gives 35.04% to 61.20% (Ca, Mg)₃P₂O₈ and from 0.21% to 0.33% N. His mean phosphate content, assuming little or no magnesium, would be 24.1%, his mean nitrogen 0.28%. Voelcker's samples were evidently cleaner than those analyzed by Nesbit.

A somewhat different substance was analyzed by Dr. Giraud of Bombay, who found (Markham, 1862):

Water	6.88%
Organic matter and NH ₃	38.75
Alkali salts	6
Ca ₃ P ₂ O ₈	18.35
Sand	26.25
CaSO ₄	3.77

This material, though no poorer in sand, is obviously richer in organic matter than

were the samples analyzed by other investigators. Though rather poor in phosphorus, it could conceivably have contained a considerable amount of nitrogen.

A cargo of the stalactite deposit, mentioned by Markham, was sold in Liverpool for £8.0.0 per ton, a high price for a non-nitrogenous guano and obviously implying a very high P_2O_5 content. It is unfortunate that nothing further is known of this occurrence, which may have been mainly monetite and which suggests those of some of the islands of Lower California.

In spite of the complaints of the shipmasters, 18,053 tons of Kuria Muria guano reached Great Britain in 1858, and by the end of 1860, when exploitation was abandoned, 37,707 tons had been received in British ports. In 1859 the material seems to have been valued at £5.0.0 per ton, but rather lower prices were realized in 1860 (Great

Britain, Parliamentary Sessional Papers, Navigation, General Imports).

Owen (1857), writing of the Gulf of Masi-rah, says that "the country is populous and a great mart for salt for fishermen and sea fowl dung." From within Kasirah Island he was told that a southwest course leads direct to Gherirat ul Humr or Hummer Island. Vessels from the Red Sea are said to go annually to ul Hummer for fowl's dung. The locality has not been identified.

THE BAHREIN ISLANDS

LATITUDE $25^{\circ} 31' N.$, LONGITUDE $51^{\circ} 00' E.$

In the Persian Gulf, described by Edrisi (1154) as numerous islands inhabited only by birds whose dung was transported to Basra and sold at a high price as a fertilizer for date palms, vines, and gardens generally. Modern information about guano islands in the Persian Gulf is not forthcoming.

PHOSPHATIC GUANO ON THE ISLANDS OF THE ATLANTIC OCEAN AND ADJACENT SEAS

ISLANDS OF THE SOUTHEASTERN TROPICAL ATLANTIC

THOUGH SUPERFICIAL PHOSPHATIZATION of igneous rock is known at Ihleu das Cabras, Sao Thomé, only two islands, namely, Ascension Island and St. Helena, have yielded significant quantities of guano. Both islands lie in the zone of the southeast trade winds, but St. Helena, lying farther south, is slightly cooler than Ascension and has a considerably greater rainfall. The relevant meteorological data are as follows (United States Hydrographic Office, 1932a):

Ascension Island, 16.8 meters above sea level
Mean air temperature, 25.0° C.; extremes, 19.4°–34.4° C.

Mean annual precipitation, 155 mm.

St. Helena (Jamestown), 12.2 meters above sea level

Mean air temperature, 21.7° C.; extremes, 14.4°–33.9° C.

Mean annual precipitation, 1090 mm.

On both islands the highest peaks receive more rainfall than is experienced at sea level. Both islands lie in the path of the South Equatorial Current, though the rather indefinite tropical convergence in this current lies between them. Hentschel notes a considerable enrichment of plankton in the vicinity of St. Helena. This is attributed to the effect of land drainage. No station was taken within 96 kilometers of Ascension, but some enrichment of the plankton at this station, perhaps due to upwelling caused by the base of the island constituting an obstacle in the course of the current, was noted. Both islands lie in a part of the Atlantic in general very poor in birds (fig. 41). At least the large population of *Sterna f. fuscata* that breeds on Ascension must scatter widely when not nesting, though its distribution in the tropical Atlantic out of the breeding season has never been established.

ASCENSION ISLAND

LATITUDE 7° 57' S., LONGITUDE 14° 22' W.

A volcanic island about 11 kilometers in diameter and with an area of 98 km². It is said to consist of 40 distinct volcanic cones.

The highest point on the island reaches 858.6 meters above sea level. The geology has been well described by Daly (1925). Most of the island is very arid and barren, though some introduced plants are grown on the summit of Green Mountain, the high hill in the center of the island. An extinct flightless rail was observed on the island by Peter Mundy in 1656 (Kinneir, 1934), but its presence hardly implies the former existence of arboreal vegetation.

The main nesting sites of Ascension Island at the present time are Boatswain Bird Island off the northeast coast of the main island, and in the southwestern part of the main island, where several immense colonies of *Sterna f. fuscata* constitute the Wideawake Fairs described by many travelers (fig. 72).

Boatswain Bird Island (pl. 15, fig. 1) is an islet of area about 8000 m²; it forms a relatively level tableland with steep sides. The cliffs are apparently occupied by *Anous minutus atlanticus* Mathews, *Phaeton a. aethereus* Linnaeus, and *P. lepturus ascensionis* Mathews. The flat interior of the island is the only breeding place of the endemic Ascension Island frigate bird, *Fregata aquila* (Linnaeus), and is also occupied by *Sula l. leucogaster* (Boddaert) and *S. d. dactylatra* Lesson. The relative numbers of the two boobies have been estimated differently by various observers; Penrose (1879) seems to imply that Gill, in 1877, found *S. l. leucogaster* to be at least as common as *S. d. dactylatra*. It was present in considerable numbers, and "in company with the other inhabitants of Boatswain Bird Island," had covered the surface of the interior with a few inches of guano. Simmons (1927) found most of the boobies to be *S. d. dactylatra*. It is possible that there are seasonal changes in the sizes of the two populations. *Anous s. stolidus* (Linnaeus) and *Gygis a. alba* also have colonies on the island. All these still appear to flourish on Boatswain Bird Island (Chapin, 1946).

The Wideawake Fairs are immense colonies of *Sterna f. fuscata*. Penrose indicates

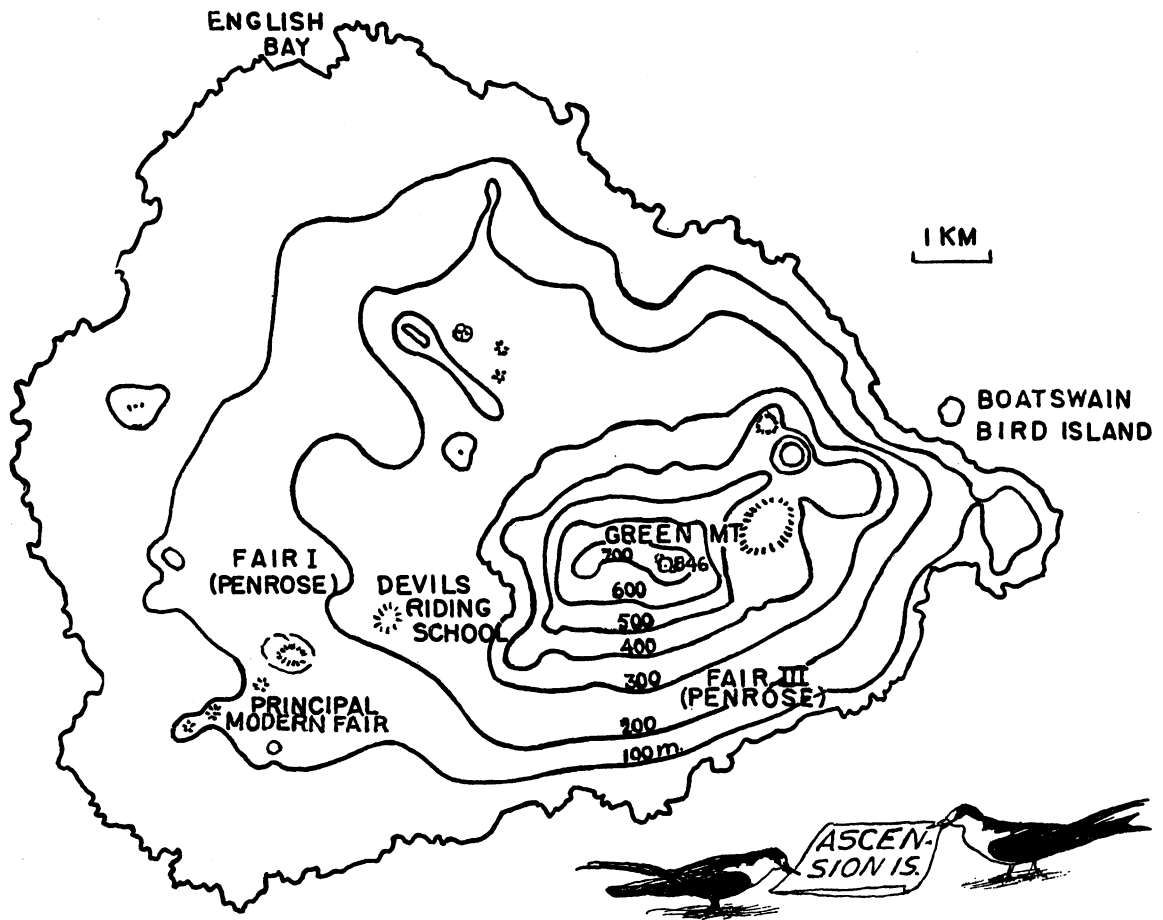


FIG. 72. Map of Ascension Island.

one site in a depression running directly westward from Green Mountain to the sea, north of the crater termed the Devils Riding School, a second site south of the first, on the southern side of a line of craters running southwest from the Devils Riding School, and a third site southeast of Green Mountain. The second of these fairs is apparently the one described by Chapin as the region preferred above all other parts of the island in recent years. The breeding time of the sooty tern on Ascension is apparently not determined by the ordinary seasonal rhythm. It has long been supposed that the birds return at eight- or nine-month intervals, though some writers appear to be skeptical of this. Chapin says that the mean time between occupation of the Fairs in 1941-1946 was 9.3 months. He gives no data permitting a judgment of the regularity of the event,

though it apparently has been very regular in recent years (Chapin, verbal communication).

Chapin estimated that each pair of birds occupied 0.60 to 0.65 m² of the Fair. Information that he received from residents on the island indicated a total population of from 1,000,000 to 2,000,000 birds. The main colony overlapped a tract that had been chosen, out of the breeding season, as the site of an airstrip, and the returning birds constituted a great hazard to military aviation. Chapin gives an interesting account of his successful efforts to induce this part of the colony to move elsewhere by the systematic breaking of their eggs. One egg is normally incubated; Chapin found one nest in 70 to contain two eggs. Nest recognition is apparently by small-scale landmarks, mainly stones around the slight depression.

Collingwood (1867) remarks on the fact that though the Fair seen from above looks as if it had been whitened by a light fall of snow, no permanent guano layer develops on the site. Chapin says that at times of abnormal rain large sections of the colony may be washed away. It seems probable that the main cause of the lack of accumulation is that the birds do not produce enough guano on the nesting sites and do not breed closely enough together to provide a thick enough annual deposit to withstand occasional inundations. Rare individual falls of rain as great as 66 mm. have been recorded.

The known occurrences of guano deposits on Ascension Island are inadequately described. The coating on Boatswain Bird Island has already been mentioned. Murphy (1936), without giving his authority, states that *Phaeton a. aethereus* nests "in holes burrowed through the accumulated guano of the main island." Simmons (1927) states that on the northern corner of Ascension, where the clinker plain meets the sea, a hundred men from St. Helena were employed, in the 1920's, in digging guano from great pits in the clinker. He speculates on whether this was produced by a colony of boobies, frigate birds, and terns like that on Boatswain Bird Island or by extinct species. It is evidently not the product of a contemporary colony. No analyses appear to have been published. The "Sailing directions for the southwest coast of Africa" (United States Hydrographic Office, 1932a) warn mariners against mistaking the lights of the "guano collecting station" at the head of English Bay for those of Georgetown. This location corresponds with that described by Simmons.

Richards (1928) found a specimen of basalt from a low pressure-dome cavern on Ascension to be coated with a crust of phosphate. This proved to be composed of newberyite, $\text{MgHPO}_4 \cdot 3\text{H}_2\text{O}$, on the outside, then a layer of a collophane-like apatite, with monetite on the inside (Fron del, 1943). This occurrence is obviously of avian origin.

According to the British statistics of imports (Great Britain, Parliamentary Sessional Papers, Navigation and Shipping, Principal Imports and Exports), 1116 tons of Ascension Island guano reached Great Britain in 1851 and 1852.

ST. HELENA

LATITUDE $15^\circ 28'$ S., LONGITUDE $5^\circ 42'$ W.

A pyramidal volcanic island about 17.5 kilometers long and 10 kilometers wide, rising to a maximum elevation of 818.4 meters. The geology of the island has been described by many older authors, among whom Darwin (1844) may be mentioned as the most important, and in recent years has been the subject of an admirable paper by Daly (1928). Among the physiographic matters discussed by Daly, it is desirable to point out that he suspects that the strong sea-cliffing on the leeward shore of the island and the apparent West Indian affinity of some of the littoral mollusks indicate that formerly the island lay, not in the trade wind belt, but in the path of winds and current from the west. Analogous cliffing on leeward shores is known in the Hawaiian Islands.

St. Helena, when discovered, was forested, but goats liberated on the island destroyed the greater part of the original vegetation. Both flora and fauna were remarkable for the number of endemic species present. The only native land bird, however, seems to have been the wire bird, *Charadrius sanctaehelenae* (Harting). Murphy (1936) summarizes the available information as to the marine avifauna of St. Helena. The following species appear to be resident: *Oceanodroma castro*, *Phaeton aethereus*, *Sterna fuscata*, *Anous stolidus*, and *Gygis alba*. In addition it is known that a species of *Fregata* formerly inhabited the island. Barnes (1817) speaks of the frigate bird as a "large dark-colored bird, its length from three to four feet, and ten to fourteen feet in width, from the extremities of the wings." By 1875 when Mellis wrote, the species, though known to have been abundant in the past, had practically disappeared; the cause of its extirpation was not apparent. Murphy states that he has never been able to find a specimen from St. Helena in any museum and is therefore uncertain if the bird was *Fregata aquila* as at Ascension; *F. minor*, represented by *F. m. nicolli* Mathews at South Trinidad and Martin Vas Islands; *F. ariel*, represented by *F. a. trinitatis* Ribeiro at the same islands; or *F. magnificens*, represented by *F. m. lowei* Bannerman at the Cape Verde Islands and

Gambian coasts. Murphy gives the following measurements of total length for the first three forms, and Bannerman (1928) for the fourth:

	MALE	FEMALE
<i>F. aquila</i>	891 mm.	960 mm.
<i>F. aquila</i> (after Barton, mean of 5)	910	—
<i>F. minor nicolli</i>	950	990–1030
<i>F. ariel trinitatis</i>	740	820
<i>F. magnificens lowei</i>	978	Presumably larger

The measurements given by Barnes correspond to 910 to 1220 mm. They are admittedly rough; the wide variation is presumably due to failure to distinguish the sexual dimorphism in size. They seem definitely to rule out *F. ariel*, all races of which are small, and perhaps suggest *F. minor* rather than *F. aquila*, a conclusion in accord with zoogeographical evidence, as already indicated by Murphy. The zoogeographically less probable *F. magnificens*, all races of which are large, cannot, however, be excluded.

Murphy, largely on the basis of a statement of Mellis that boobies frequent the seas around the island, though seldom coming to land, lists *Sula* sp. as one of the former inhabitants and concludes that *Sula sula* probably bred on the arboreal vegetation of the island in its virgin state. Barnes, who correctly lists the red-billed tropic bird, the "white bird," "black-bird," and "egg-bird," the noddy, the petrel, and the wire bird, says nothing about boobies. It is probable that both his black bird and egg bird are *Sterna fuscata*, while his white bird is obviously *Gygis alba*.

St. Helena appears to have extensive deposits containing fossil or subfossil bird bones. It is a sad and scandalous fact that no proper study of these bones has ever been undertaken.

Barnes (1817, p. 64) writes that on a hill adjoining the eastern coast a considerable bed of limestone consisting of abraded shells, minute black fragments, and other material contained at a depth of 14 feet a number of small eggshells, while "the superstratum which rests upon the limestone is a dark friable earth, two or three feet in depth in which are deposited numbers of small bones and fragments of egg-shells, some of which

appear to be as large as a common hen's egg. There are no bones in the stratum of limestone."

Seale (1834) notes what may be the same deposit in a natural amphitheater between Holdfast Tom and Prosperous Hill Bay. The deposit containing the bones is said to have extended from the water's edge to about a mile inland and was 3 to 30 meters deep. The bones were identified as belonging to red-billed tropic birds and wandering albatrosses. The former attribution is reasonable; the latter is not. The larger bones may well have been those of *Fregata*.

Both Darwin and Daly examined a sand poorly cemented with calcium carbonate and apparently representing an ancient sand dune, lying 300 meters east of the summit of Sugarloaf Hill on the northern coast of the island. The sand lies on eroded basalt in a col opening directly on the sea cliffs. Darwin found land shells, bird bones, and eggs in this deposit.

Blofeld (1852) records bird bones from half a mile behind Longwood, at an altitude of about 520 meters above sea level. The profile here consisted of "5 to 6 feet of dark mould, and under this . . . a stratum of a greyish-brown friable earth about 3 to 4 feet thick." The grayish brown earth contained abundant extinct land shells, and bird bones both perfect and fragmentary. It also contained lumps of a white powdery substance, associated with a harder yellow substance. The white material was mainly calcium carbonate and sulphate, with magnesium carbonate and ferric phosphate. The yellow material had a similar composition but contained organic matter. No quantitative data were published. Owen examined the bird bones but reported merely that they belonged to sea birds. At the same time he indicated that bones collected from a grayish brown earthy deposit, containing sand grains coated with lime, by Captain Wilkes, R.N., at Turk's Cap Bay, which is probably the same as Prosperous Bay, included material of *Puffinus* sp. These bones may have come from Seale's locality, which is possibly the same as that described by Barnes. Mellis also refers to fossil bird bones, but the more recent authors discussing the island have added no new information. It is perhaps of interest that

all the localities where bird bones have been found are in the eastern half of the island.

The first indication of guano deposits on St. Helena is given by Beatson (1816) who, in 1811 when governor of the island, obtained guano at the suggestion of Sir Joseph Banks and applied it to the culture of "*mangel wurzel*" which is the white or sugar beet" with great success. He also appears to have used the same fertilizer on other crop plants. According to Kitson (1931), Beatson recorded that considerable amounts of guano occurred on Egg Island, an islet off the western coast of St. Helena. Kitson also states that Janisch (1885) found a record of specimens of guano being sent from Egg Island to England as early as July 16, 1808. From the British import statistics (Great Britain, Parliamentary Sessional Papers, Trade and Navigation) it appears that St. Helena guano was brought to British ports intermittently between 1844 and 1860. The last two cargoes, landed in 1855 and 1860, respectively, realized from £4.0.0 to £5.0.0 per ton, sug-

gesting a quite good phosphatic guano. In all, 4908 tons were received during the period indicated.

Kitson states that Gallwey (*sic*) in the Report of the Governor of the Island to the Colonial Office, records in 1907 that a Mr. Cannon, phosphate expert of the firm of Jas. Morrison and Company, made 400 analyses of samples of supposed phosphate but regarded the results as unfavorable. Mr. Herdsman, a manganese expert, considered, however, that good old guano existed on the eastern side of the island. Daly records that at Prosperous Bay a thin layer of brown phosphate, covering lateritized basalt, probably represents the site of an old bird colony.

IHLEU DAS CABRAS, SAO THOMÉ

LATITUDE 0° 25' N., LONGITUDE 6° 43' E.

An islet off the northern coast of Sao Thomé recorded by Lacroix (1906) as exhibiting the direct alteration of a trachyte into aluminum phosphate. No analysis is given.

ISLANDS OF THE CARIBBEAN AND CAYMAN SEAS

A number of localities in the West Indies (fig. 73) have yielded phosphatic guano. The distribution, history, and geochemistry of such deposits provide interesting problems.

CLIMATOLOGY

The whole region lies in the latitudes of the northeast trade winds. Air temperatures are in general high, averaging over 25° C. throughout the year. Rainfall at sea level is moderate to low. The greater part of the Greater Antilles and the northern Lesser Antilles fall within the 1000-mm. isohyet. The southern members of the Lesser Antilles receive less rain, but the precipitation is very dependent on local factors, elevated islands receiving more than flat ones. The Venezuelan and Dutch West Indian coastal islands are dry, the rainfall not exceeding 560 mm. and in some localities being considerably less.

OCEANOGRAPHY

The oceanography of the Caribbean and Cayman seas is complex (cf. Parr, 1937). In general, surface temperatures are high, the

mean value being around 27° C.; corals flourish throughout the region. Most of the surface water is derived from the tropical Atlantic, but the exact point of entry is apparently variable. The tropical oceanic origin of this water is clearly responsible for the general low productivity of the region. Rakestraw and Smith (1937) found that in the central part of the Caribbean the phosphate content at the surface was very low, less than 0.1 milligram-atom per liter, but that higher values were observed in the Cayman Sea, along the Venezuelan coast, and in the region of the Lesser Antilles. The nitrate distribution was quite different. Minimal values were found along the Venezuelan coast, maximal in the northwestern part of the Cayman Sea. The minimum in the southern part of the region is probably due to increased biological consumption in this part of the area.

Off the Guianas and Venezuela, the South Atlantic Equatorial Current flows coastwise for some distance, through a region receiving considerable land drainage. The resultant access of nutrient salts of terrestrial origin

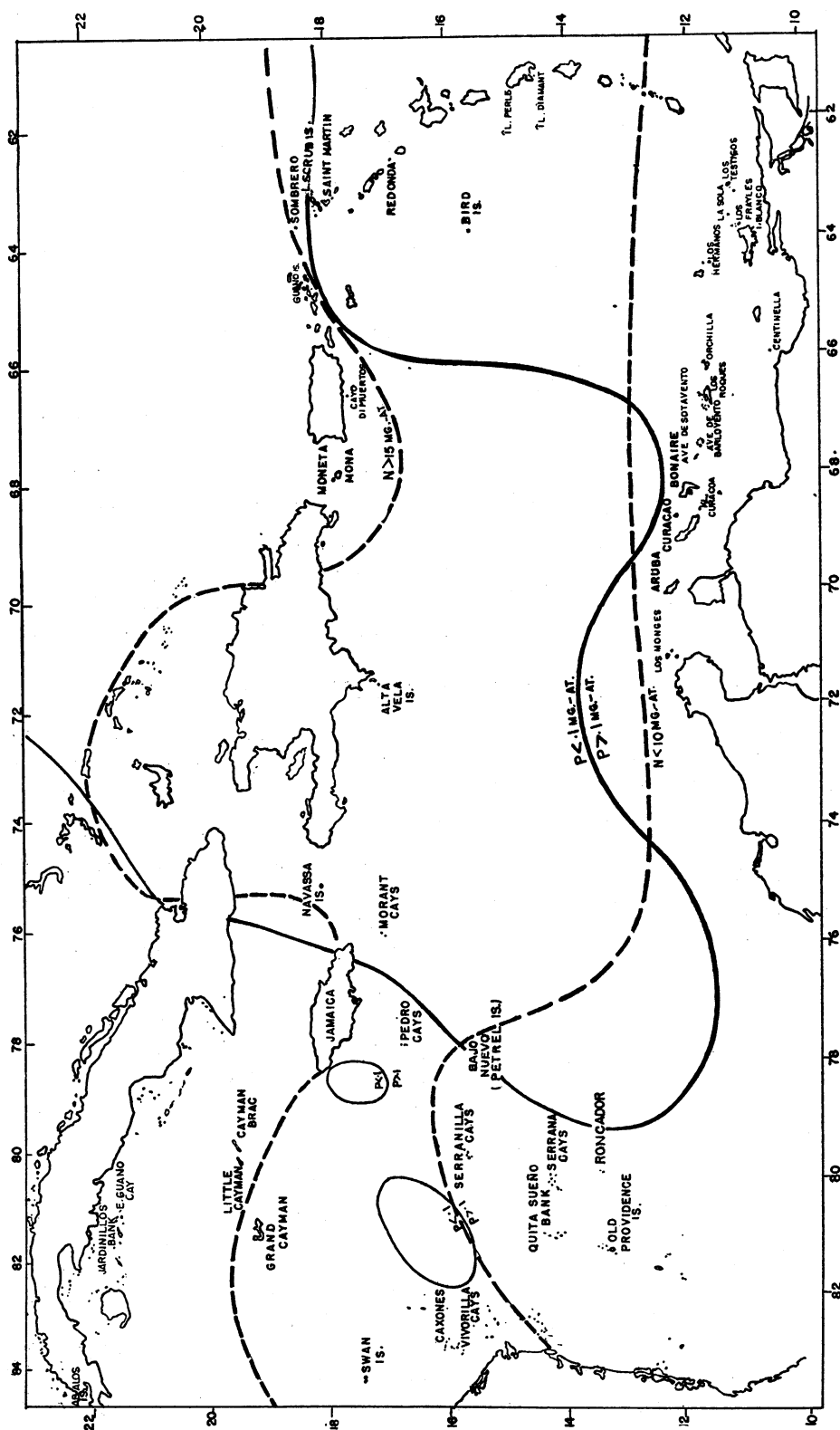


FIG. 73. Map of the Caribbean and Cayman seas showing distribution of guano islands and of nitrate nitrogen and phosphate phosphorus in the surface layer of the sea.

is reflected in the higher biological production of this region, rather than in accumulation of unutilized nitrate. Thompson (verbal communication) suspects that upwelling on the southern edge of the North Equatorial Current may also be involved in enrichment of the water flowing along the Guianan and Venezuelan coasts. It is interesting to note that, according to Brown (1942), fishermen at Barbados believe that the junction between blue oceanic and green littoral water is often specially productive, as is the case off Peru. Within the 200-meter contour off the Venezuelan coast there is a coastal counter current, and there is probably a complex current pattern around the Venezuelan Leeward Islands, leading to vertical mixing as well as nutrient transport from the east (Fiedler, Lobell, and Lucas, 1943b). The relatively high productivity of the area is well indicated in the general fisheries statistics published by Fiedler, Lobell, and Lucas (1943b). Although the Venezuelan coast occupies perhaps one-sixth of the coast line that they considered, its fisheries account for an estimated 100,000,000 out of the 161,000,000 pounds landed annually throughout the region. The best Venezuelan fishing grounds are around the Venezuelan Leeward Islands, some of which are considered as phosphatic localities below.

There are also productive fishing grounds along the Central American coasts of the regions under consideration. These grounds owe their existence largely to land drainage. The only phosphatized localities recorded in this part of the area are Vivorilla Cays. The Honduras-Jamaica ridge between the Caribbean and Cayman seas is marked by shallow banks, which are frequented by fishermen. According to E. F. Thompson (verbal communication), the Serrana Bank is particularly productive. The hydrographic conditions on the banks bounding and within the Cayman Sea are evidently very variable and complex. Much more vertical movement can clearly be expected than in the central Caribbean. Parr indicates a large eddy south of Jamaica, and there may well be local upwelling on the productive banks. Similarly farther north a complex eddy south of Cuba and an influx of water from the Gulf of Mexico flowing southeast from the western

tip of Cuba probably introduce hydrographic complexities that may result in local upwelling. The productive western grounds are largely fished by Cayman islanders, whose knowledge surpasses that of other fishermen of the region (Fiedler, Lobell, and Lucas, 1943a).

Between Hispaniola and Puerto Rico the Mona Channel provides somewhat better fishing than might be expected in this generally unproductive part of the Antillean arc, and this is probably associated with local vertical mixing (E. F. Thompson, verbal communication).

ORNITHOLOGY

As far as it is possible to ascertain from the literature, the most important guano birds of the West Indies are the boobies, *Sula d. dactylatra* Lesson and *S. l. leucogaster* Boddaert. Several thousand pairs of *S. leucogaster* congregate to breed on Middle Cay of the Pedro group, along with 50 to 100 pairs of *S. dactylatra*, according to C. Bernard Lewis (*in litt.*). He writes: "I understand that the guano deposit on this Cay is better than on the other Cays, and I am told that *Sula dactylatra* produces a superior guano, while that of *Sula leucogaster* is considered valueless." Elucidating the latter statement he indicates in a later letter that *S. leucogaster* spends less time at the nesting site than does *S. dactylatra*, and that the nesting period of the former is limited to April and May, while the latter species is nesting for a period of six to eight months. Ludwig (*in Sievers*, 1898), one of the few observers who have published information on contemporary guano formation in the West Indies, states that on one of the islets of Ave de Barlovento boobies are responsible for the deposit. Cory (1909) notes only *S. leucogaster* from Ave de Barlovento, where it was common, breeding at the end of January. It is not improbable from Barnés' (1946) observations, that the same species has contributed much guano to the cave deposits on Mona Island.

At present the three boobies are clearly restricted in the number of their breeding grounds. In the Venezuelan Leeward Islands Cory records *S. l. leucogaster* on Ave de Barlovento, Los Hermanos, and Testigos, *S. s. sula* on the two last named, and *S. d.*

dactylatra only on Los Hermanos. Murphy (1936) indicates that the last-named species occurs on Alacrán and other low sandy reefs in the Gulf of Mexico. In the past it is not unlikely that these birds had different nesting sites, varying with the emergence of the land and other ecological factors. Old phosphate deposits not improbably represent old colonies of the two ground-breeding species of *Sula*. *Sula s. sula* (Linnaeus), which breeds exclusively in bushes and small trees, is limited in its distribution by this requirement, occupying sites where accumulation is not very likely to take place.

Terns, notably *Sterna f. fuscata*, *S. anaetheta melanoptera* Swainson, and *Anous s. stolidus* (Linnaeus) form considerable colonies and might be expected to have produced significant accumulation of guano. C. Bernard Lewis (*in litt.*), however, indicates that on Morant Cays, where the first and third of these birds breed, the guano deposits are poor, and the birds are mainly exploited for their eggs. *Fregata magnificens rothschildi* Mathews may be locally of some significance. Its numbers presumably are to some extent limited by the number of other sea birds that it can rob, though it has a much wider distribution in the Venezuelan Leeward Islands than have the boobies. *Pelecanus occidentalis*, known from all the Venezuelan and Dutch Leeward Islands save the Islas de Aves and Los Hermanos (Cory, 1909), is a possible contributor in the southern part of the Caribbean region.¹

Apart from the data supplied by C. Bernard Lewis, the only population study that gives any idea of the relative number of sea birds in the region is that conducted by Wetmore (1927) on Desecheo Island, which is not an important locality for guano. In 1912 he estimated the population, late in the breeding season, to have consisted of:

<i>S. l. leucogaster</i>	8,000-10,000
<i>S. s. sula</i>	2,000
<i>Anous s. stolidus</i>	2,000
<i>Sterna anaetheta melanoptera</i>	1,500
<i>Fregata magnificens rothschildi</i>	175

In later years the brown booby population apparently declined.

DESCRIPTION OF THE ISLANDS

It is convenient to consider the localities in four groups:

- Islands in the Cayman Sea and the western reefs of the Caribbean
- The Greater Antilles and associated islands
- The Lesser Antilles
- The Venezuelan and Dutch Leeward Islands

ISLANDS IN THE CAYMAN SEA AND THE WESTERN REEFS OF THE CARIBBEAN

It is convenient to start a survey in the southwestern part of the region, beginning with two little-known groups of deposits and then passing to the Swan and Cayman Islands, to the west of the true Caribbean, and to the islets on the reefs that separate the latter from what Parr (1937) has termed the Cayman Sea. In general, all of these islands and reefs represent limestone-crowned submarine peaks. At least the Cayman Islands indicate two periods of emergence, separated by limited coastal submergence in the Pleistocene or Recent, comparable to that known along the shores of the Greater Antilles. Climatological data are meager, but the rainfall on Grand Cayman Island is reported as about 1956 mm. per annum (United States Hydrographic Office, 1922), a rather high value for sea level in the West Indies, and on Swan Island as about 1300 mm. per annum. The mean annual temperature at the latter station is 26.95° C., the observed extremes being 17.8° C. and 33.3° C. (Reed, 1926).

OLD PROVIDENCE ISLAND

LATITUDE 13° 19' N., LONGITUDE 81° 23' W.

A high island rising to an altitude of 302.7 meters and with a maximum length of rather over 7 kilometers. The island is said to be extremely fertile (United States Hydrographic Office, 1927c). The only evidence that guano

¹ *P. o. occidentalis* Linnaeus occurs throughout the greater part of the Caribbean region, perhaps intergrading with *P. o. carolinensis* Gmelin in Cuba. The latter bird follows the coast of the Gulf of Mexico around through Central America to the southern shores of the Caribbean. *P. o. occidentalis* is certainly found in Aruba and probably in Curaçao and Bonaire. It is uncertain which race inhabits the Venezuelan Leeward Islands (Wetmore, 1945).

has occurred here is a decree promulgated at Cartagena in 1854 prohibiting the extraction of guano from "the deposit recently discovered in the district of Providence or any other which may hereafter be discovered in the group of islands which compose the canton of San Andrés." This decree is printed in translation with a covering letter by Charles E. Kortright, British Consul at Cartagena, Colombia, to the Earl of Clarendon in Great Britain, Parliamentary Sessional Papers, 1854-1855. The occurrence must be regarded as highly problematical.

VIVORILLA CAYS

LATITUDE 15° 52' N., LONGITUDE 83° 20' W.

Also apparently called Vivario Cays, a group of several low coral cays on the Miskito Bank. They support numerous trees and bushes. To the northwest there is a similar group called the Caxones or Hobbies. According to a report of Capt. Henry Coryton, included in a letter from Rear Admiral Arthur Fanshawe to the Secretary of the Admiralty, dated May 10, 1856 (Great Britain, Parliamentary Sessional Papers, 1857) an American bark "Rhoderic Dhu" (Capt. L. Bryant) of 300 tons was loading guano at the Vivorilla Cays. The work was difficult and after six weeks she was but two-thirds loaded. The guano had to be dug into for 2 or 3 feet and sifted. A stranger on the cays would not realize the material to be present. Captain Bryant had obtained guano previously at the Vivorilla Cays, and a Captain Patterson of New York was said to have worked the Hobbies, as had people from the "Caymanes." Ullmann lists Vivorilla guano as phosphatic but without an analysis or other details.

THE SWAN ISLANDS

LATITUDE 17° 25' N., LONGITUDE 83° 56' W.

Between Great Cayman and Honduras are a pair of small islands, the larger rather over 3 kilometers long and of maximum altitude of about 18.3 meters above sea level. They are, at least in part, raised coral islands (Schuchert, 1935), though an exposure of shale and a material like Fuller's earth appear to occur on Great Swan under the coral cap

(Lowe, 1911). The larger island was originally heavily wooded. Lowe, who gives a general description, indicates that considerable clearing was made at the eastern end of Great Swan by phosphate diggers. Some portions of the surface phosphate were reduced in value by intermixture of organic soil derived from the leaves of trees (Pacific Guano Company, 1876). Three types of phosphatic guano are said to have been present, an upper soft earthy layer, dark brownish in color, containing phosphate equivalent to about 60% $\text{Ca}_3\text{P}_2\text{O}_8$; a semipetrified guano, of light brown color comparatively free from water and containing the equivalent of 55% to 60% $\text{Ca}_3\text{P}_2\text{O}_8$; and a compact phosphate rock, brown or opaque white, yielding the equivalent of 75% to 80% $\text{Ca}_3\text{P}_2\text{O}_8$. These chemical data, given by the Pacific Guano Company, doubtless were optimistic. The total quantity present was estimated in 1858 by a United States Government commission as 3,000,000 tons. Analyses were also published by Nesbit and by Dietrich, neither of whom seems to have had the best material submitted to him.

Nesbit gave:

H_2O	9.28%
Organic matter	11.74
CaO	19.15
$(\text{Al,Fe})_2\text{O}_3$	16.12
$(\text{Al,Fe})\text{PO}_4$	2.23
P_2O_5	14.52 (= 31.70% $\text{Ca}_3\text{P}_2\text{O}_8$)
CO_2	1.23 (= 2.79% CaCO_3)
SO_3	0.64 (= 1.33% $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)
Alk. salts	2.92
SiO_2	22.15

Dietrich found:

H_2O	13.50%
Organic matter and NH_3	13.66, of which 0.57% N
Earthy phosphates	40.0
Sand, gypsum, etc.	32.84

For a predominantly coral island the amount of iron and aluminum found by Nesbit is high.

Lowe says there is also a deposit of phosphate at the eastern end of Little Swan Island. This smaller island, the surface of which is much fissured, has breeding colonies of *Sula l. leucogaster* (sub *S. sula*) nesting on rough ground covered with *Sesuvium*, and of

S. sula (sub *piscator*) and of *Fregata*, presumably *F. magnificens rothschildi* Mathews, nesting in the more overgrown parts of the island. It seems probable that the island is now too richly vegetated to accumulate much phosphate as discrete deposits.

THE CAYMAN ISLANDS

A group of three elongate islands: Cayman Brac (latitude 19° 41' N., longitude 79° 53' W.; 19.4 kilometers long and 2.6 kilometers wide), Little Cayman (latitude 19° 40' N., longitude 80° 05' W.; 16.6 kilometers long and 1.8 kilometers wide), and Grand Cayman (latitude 19° 16' N., longitude 81° 20' W.; 37 kilometers long and 15 kilometers wide).

The geology of the group has been well described by Matley (1926), who has also contributed a short account (1928) of the phosphate deposits. The islands stand on an ancient mountain axis, the emergent parts of which are covered with Tertiary limestones, of middle Oligocene age on Cayman Brac, of lower Miocene in the cases of the other two islands. There is a narrow coastal shelf due to marine planation of these limestones, on which a Pleistocene Ironshore formation was deposited. This deposit is composed of cemented coral sand with coral heads; it now lies 4 to 5 meters above sea level. The weathering of the calcareous rocks of the islands has produced a limited amount of reddish residual soil. The phosphate deposits occurred in pockets or pot-holes. They were found on the Ironshore formation of Grand and Little Cayman, and on the Tertiary limestone also, on Cayman Brac. On Cayman Brac, apart from the occurrence on the limestone forming the plateau of the island, there was a deposit at the west end, on Grand Cayman a deposit near Georgetown in the northwest end of the island, on Little Cayman a deposit at the west end of the island. It appears that the promontories at the western or lee ends of the islands were specially favored.

Matley (1928), on the basis of an account of the history of the Cayman Islands phosphate trade in Hirst's "History of the Cayman Islands" (a work that it has not been possible to consult), states that 430 tons of phosphate were exported to New York in 1884 and that work continued until 1890.

The poor quality of much material exported was attributed to the ignorance of the people collecting the phosphate. Earthy phosphate from Grand Cayman contained 19.5% P_2O_5 , rock phosphate 23.59% P_2O_5 . Matley himself collected material from the bluff at the east end of Cayman Brac containing 19% P_2O_5 and from old dumps at the west end of Cayman Brac and on Little Cayman Island a somewhat better grade containing 25.25% to 26.25% P_2O_5 . It is clear that the phosphate contained a good deal of $CaCO_3$, and iron and aluminum are said to have been present. C. Bernard Lewis (verbal communication) informs me that at the present time *S. sula* breeds on Little Cayman, while no species of the genus at present occupies Grand Cayman. On Cayman Brac *S. leucogaster* occupies the entrances of caves in the bluff of Tertiary limestone, mainly at the eastern end of the island. Maynard (1889) states that *S. sula* was encouraged on Little Cayman as they gradually killed the trees on which they nested, so permitting the planting of coconuts in the clearings that the birds had thus made and enriched with bird droppings. C. Bernard Lewis (verbal communication) tells me that some phosphate is still imported from Cayman Brac to Falmouth, Jamaica.

RONCADOR, QUITA SUEÑO, SERRANA CAYS, SERRANILLA CAYS, AND BAJO NUEVO

Banks, parts of which are just emergent above high-tide mark, lying between Jamaica and Honduras. According to Schuchert (1935), they are limestone-covered volcanoes, which appear to be structurally associated with Jamaica.

Palmer (1900), on the basis of information on file in the United States Treasury Department, lists the following "guano islands" in this region as claimed by the United States. The data as to emergence are taken from the United States Hydrographic Office charts 373, 394, and 945 and from the "Central America and Mexico pilot" (United States Hydrographic Office, 1927c).

Roncador (latitude 13° 33' N., longitude 80° 03' W.), emerging 4 meters

Quito Sereno (latitude 14° 30' N., longitude 80° 07' W.) = Quita Sueño of charts; hardly emergent

Serrana Cays:

- Anchor Key (latitude 14° 18' N., longitude 80° 08' W.), not identified on chart
 Booby Key (latitude 14° 14' N., longitude 80° 30' W.), not identified on chart
 North Keys (latitude 14° 25' N., longitude 80° 20' W.), emerging 0.9–1.5 meters
 North Rocks (latitude 14° 20' N., longitude 80° 26' N.), Northwest Rock of chart, emerging 0.6 meter
 Serrana Key (latitude 14° 15' N., longitude 80° 24' W.), probably Southwest Key of chart, emerging 9.7 meters
 Triangle Keys (latitude 14° 20' N., longitude 80° 05' W.), not identified on chart
 Serranilla Cays (latitude 15° 20' N., longitude 79° 40' W.), comprising:
 East Cay, emerging 2.1–2.4 meters
 Middle Cay, emerging 2.1 meters
 Beacon Cay, emerging 2.1–2.4 meters
 Petrel Island (latitude 15° 52' N., longitude 78° 33' W.), apparently Low Cay, Bajo Nuevo, emerging 1.5 meters

It is well known that many more islands were claimed and listed with the United States Treasury than actually contained guano. Some of these islands may therefore not actually have borne guano. There is, however, independent evidence indicating deposits on certain of them.

RONCADOR CAY

About 560 meters long by 230 meters wide, composed of sand with a wall of coral boulders on the northwest side. It is devoid of trees and bushes. The "Central America and Mexico pilot" (United States Hydrographic Office, 1927c) states that guano was formerly obtained on Roncador Cay.

Voelcker (1876) analyzed a sample of phosphatic guano from "Quito Serrano." Examination of the charts and the "Central America and Mexico pilot" indicates that Quita Sueño, which might be suspected as the source of the material, is the least likely of the emergent banks in this region to possess a deposit. The reef is said to be dry in places, and tree trunks and other material were described as accumulating on the reef so that it was "probable that a cay would be formed there at no very remote period." Yet in 1926 only the light tower and a sharp rock were permanently emergent. In view of the uncertain orthography and the restricted

land surface of Quita Sueño, it seems probable that Voelcker's material actually came from one of the Serrana Cays.

In the same year as Voelcker's analysis was published, 950 tons of guano, valued at \$5432, were brought to the United States from Serrana Cays. The price is very low and implies an inferior material. No other records of importation appear to exist. (Annual Reports on the Commerce and Navigation of the United States, United States Bureau of Statistics.) C. Bernard Lewis (verbal communication), however, believes that phosphatic guano is still brought from the Serrana Cays to Falmouth, Jamaica.

Voelcker gives another analysis, of material from Petrel Island, which probably came from Bajo Nuevo or Low Cay, the position of which corresponds to that given for the Petrel Island of the United States Treasury list. This cay is 274 meters long and 46 meters wide, with a small pond frequented by seals. The surface is barren, composed of coral, sand, and driftwood.

Voelcker also gives an analysis from Booby Island, which may refer to the Serrana Cay of that name listed by Palmer, though there is a Booby Island off the coast of Queensland in latitude 10° 39' S., longitude 141° 55' W., and possibly also others in other regions. Voelcker tabulates his three analyses with those of phosphatic guano from Coral Island, probably in the Marquesas, and McKean Island in the Phoenix group. The arrangement of the tabular material therefore has no geographical basis, and the Petrel and Booby Islands analyses can obviously not be assigned to the cays of the Cayman Sea with complete confidence.

	"QUITO SER- RANO"	PETREL	BOOBY
H ₂ O			6.10%
Organic matter }	8.50%	9.51%	10.18
CaO	39.41	36.44	45.36
MgO, SO ₃ , CO ₂ , alk.	17.10	18.05	16.50
P ₂ O ₅	32.44	30.50	21.77
Insoluble siliceous matter	2.55	5.50	0.09

The molecular ratio CaO:P₂O₅, perforce uncorrected for sulphate or carbonate, is 1:0.324 for the "Quito Serrano" sample.

PEDRO CAYS

LATITUDES 16° 57'–17.03 N.,
LONGITUDES 77° 45'–77° 50' W.

A group of four very low (2.4–3.7 meters) islets near the southern edge of the Pedro Bank, south of Jamaica. They are apparently leased as a source of guano (United States Hydrographic Office, 1927a), but C. Bernard Lewis says that the Pedro Cays are of value primarily as a source of terns' eggs and as a fisheries center. Middle Cay, with a colony of *S. d. dactylatra* as well as *S. l. leucogaster*, has the best deposit, the former bird being supposed to produce a better guano than the latter. An old analysis by Nesbit (1860) gives:

H ₂ O	17.80%
Organic	6.16
CaO	39.95
MgO	1.09
(Al,Fe) ₂ O ₃	1.00
Alkalies	0.90
P ₂ O ₅	22.21
CO ₂	9.55
SO ₃	0.89
SiO ₂	0.45
N	0.28

Allowing 1.92% gypsum and 21.71% CaCO₃, the molecular ratio CaO:P₂O₅ appears to be 1:0.324. This, however, makes no allowance for possible (Al,Fe)PO₄.

THE GREATER ANTILLES AND
ASSOCIATED ISLANDS

The large islands of Cuba, Jamaica, Hispaniola, and Puerto Rico are geologically complex. They are "composed mainly of sedimentary strata, to which, in the cores of the mountains, have been added much granite and other plutonic materials, with great volumes of Cretaceous-Eocene volcanic flows, breccias, ash and intrusives" (Schuchert, 1935, p. 396). All of the major islands show abundant evidence of Pleistocene raised beaches; around the first three, emerged coral reefs are well known. It is therefore impossible to make any general statement as to the kind of substratum on which a bird colony, either ancient or modern, is likely to have been established. Certain coastal locali-

ties on the mainland of Puerto Rico appear to have had guano deposits, and it is quite probable that this is also true of the other islands. Little information is, however, available about these occurrences. The four chief phosphate islands of the group are the small isolated islands of Navassa, Alta Vela, Mona, and Monito, all of which present features of considerable interest. The other guano deposits must have been mostly small and of only local economic importance, and many islets must have been more or less devoid of the material. While it is difficult to be certain, in view of the scantiness of the available information, it seems likely that an islet on the northern margin of the Caribbean is, other things being equal, less likely to contain guano than one on the southern margin, off Venezuela. Such a distribution, if valid, is probably in part due to the lesser rainfall in the southern part of the Caribbean, but it is doubtless mainly due to the fact that the Venezuelan coast is biologically more productive than the rest of the area.

BAHAMA ISLANDS

An anonymous statement (Anon., 1876) indicates that the total guano resources of the Bahamas were 400,000 tons, but this was certainly cave guano and was probably not avian (p. 391).

CUBA AND ADJACENT ISLETS

Various localities around the Cuban coast have certainly yielded guano, but the published information is very inadequate. East Guano Cay (latitude 21° 39' N., longitude 81° 03' W.) is described in the "West Indies pilot" as having a rough pitted surface due to guano diggings. A locality designated Avalo Island, which Dr. W. J. Clench indicates (*in litt.*) is presumably the small island at the head of Punta Abalos, Pinar del Rio (latitude 22° 11½' N., longitude 84° 27' W.), is stated (Heiden, 1887) to yield a dark powdery guano containing lumps which were white to yellowish red internally. Analysis by A. Schlimper (*in* Heiden) gave:

	POWDER	LUMPS
H ₂ O	20.12%	6.30%
Organic matter and combined water	10.96	7.29
Fe ₂ O ₃	5.88	2.97
Mn ₂ O ₄	tr.	—
Al ₂ O ₃	tr.	tr.
CaO	31.15	44.52
MgO	0.44	—
K ₂ O	0.16	tr.
Na ₂ O	tr.	0.11
SO ₃	0.10	—
P ₂ O ₅	24.36	35.43
P ₂ O ₅ water soluble	0.45	0.03
CO ₂	2.00	3.06
SiO ₂	2.42	0.07
Cl	tr.	tr.
Sand	2.41	0.25
N	0.45	0.03

An account of the occurrence of guano on the Cayos de los Jardinillos, west of the Isle of Pines, about latitude 20° 40' N., longitude 81° 30' W., was apparently published by Reinoso (1859), but his work has not been available.

Palmer (1900) indicates that "Alacran Rocks in the Carribean Sea" were abandoned as a guano source, because the value of the deposits was negligible. This may refer to Alacranes Cay, off Point Alacranes (latitude 22° 53' N., longitude 83° 27' W.).

MORANT KEYS

LATITUDE 17° 26' N., LONGITUDE 77° 55' W.

South-southeast of the extreme eastern end of Jamaica, breeding grounds for large numbers of sea birds. Eggs are collected commercially, but, according to the "West Indies pilot" (United States Hydrographic Office, 1927a, p. 360), the supply of guano is of poor quality. This is confirmed by C. Bernard Lewis (*in litt.*) who hopes to publish a full account of the Morant and Pedro Cays. He indicates that the bird colony has been affected by removal of vegetation and its modification by burning. He believes that the guano collected here was not produced by the contemporary bird colony. No analysis appears to have been published.

NAVASSA

LATITUDE 18° 25' N., LONGITUDE 75° 01' W.

A small elevated coral island set on a

submerged bank 22 to 36 meters deep. The island is pear shaped, about 3.7 kilometers long. There is a well-marked terrace which apparently slopes northwest, the cliff being 2 to 3 meters high on either side of the northwest point of the island, and up to 20 meters at the southeast end (fig. 74). D'Invilliers (1891), who gives the best description of the island, is not entirely explicit on the matter. Within the terrace the island rises steeply to the rim of a flat central area lying at about 70 meters above sea level, the maximum elevation of the rim being 78 meters. This area presumably represents the lagoon of an elevated atoll. The whole island is stated by D'Invilliers to be composed of recent coral limestone. No determinations of the fossils appear to have been made, so that the age is not adequately established. The upper part of the limestone is colored in places a deep blue, but shafts dug in the upper plateau show the main material to be a pure white, often amorphous calcium carbonate. A shaft from the plateau to just below sea level disclosed nothing but pure limestone. No analyses have been published, and there is no indication if dolomitization has taken place. The surface of the island is very irregular, being marked with cylindrical holes and narrow fissures trending north 20° west, south 20° east. Some of the holes are conical and smooth as if due to eddying water. Gaussoin (1866) noted blow holes at the top of the inner cliff. The climate appears to be dry, with no protracted rainy season. Soil is poorly developed, and no fresh water is available. The island is, however, covered with scrub palms, rank grass, cactus, large century plants, and a few species of small trees.

The phosphate deposits are purely superficial, filling the pits and fissures in the surface of the limestone. Schmidt (1921) supposes that these fissures are collapsed caves, but it is more probable that they were formed by subaerial dissection immediately after the emergence of the island and are comparable to the pinnacles and pits formed on Aldabra Island and still more strikingly on the elevated Pacific phosphate islands. In a few cases phosphate pockets extended down 10 meters and were 4 to 5 meters wide, but usually the fissures are only just wide enough

other published analyses refer in all probability to the gray material, which was commercially preferred. As far as can be ascertained, the total $(\text{Al,Fe})_2\text{O}_3$ content was always in excess of 10%. Voelcker gives two cases, presumably referable to gray phosphate, in which he separated Al_2O_3 and Fe_2O_3 , obtaining 9.11% and 9.48% of the former and 4.18% and 4.49% of the latter oxide. It would therefore appear that alumina is roughly twice as abundant by weight as is iron oxide, in both red and gray phosphates. The SiO_2 content varies from 2.55% to 6.28% in the various analyses. Nesbit records 0.21% and 0.28% N. Gaussoin (1866) states that most of the deposit consisted of spherical grains, the size of mustard seed to that of buckshot. Hard crusts lined cavities in the limestone, but he noted no crystalline material. Many bones are recorded.¹

In spite of the highly improbable statement in the "West Indies pilot" that the island contains veins of iron pyrites, D'Inville is emphatic that he encountered nothing but coral rock and phosphate on Navassa. The origin of the considerable quantity of iron and alumina in the phosphate is therefore puzzling. D'Inville supposed it to come from sea water, and therefore to be more abundant where undisturbed evaporation could occur, in the old lagoon, than on the exposed terrace. There is, however, every reason, from the known composition of sea water, to reject this view. Du Toit suggests that a residual soil was formed by the decomposition of large amounts of limestone, and that the iron and aluminum are derived from this soil.

ALTA VELA ISLAND

LATITUDE $17^\circ 28' \text{ N.}$, LONGITUDE $71^\circ 38' \text{ W.}$

An islet about 1.2 kilometers long and 0.8 kilometers wide, rising to a summit 152.4 meters above high water. Cooke (1921) shows the island of Beata as covered with alluvial deposits, but Alta Vela is obviously composed of more resistant rock. Los Frailes, a cluster of white-topped rugged rocks be-

tween Cabo Falso and Alta Vela, are presumably covered with guano. Baron de Wimpffen (1797) observed a "prodigious number of sea birds" on Alta Vela, "a mere rock, with a few green spots about it." Phosphate was worked here in the nineteenth century, but no good account of the occurrence seems to be available. Voelcker (1875) gave four analyses, one of which indicated 11.29% CaO and 4.01% CO_2 ; the other samples were free from calcium and carbonate. Alumina appears to be the principal base in all specimens, and a rather large amount of insoluble siliceous material was present. The Alta Vela phosphate is clearly the result of the phosphatization of an igneous rock, and the chemical data are discussed at greater length below.

The British statistics on imports (Great Britain, Parliamentary Sessional Papers, Trade and Navigation, 1865-1890) indicate that between 1865 and 1876 19,813 tons of guano were received from Haiti and Santo Domingo. This material was obviously mainly phosphatic guano, usually realizing £4.0.0 to £6.0.0 per ton, though the 1871 cargo was poorer and the last cargo of 560 tons received in 1876 was much richer, fetching £8.0.0, which was a very high price for a phosphate at that time. From 1871 to 1880 an aggregate of 54,537 tons of unenumerated manure, realizing from £2.12.0 to £3.18.0, were imported, and from 1882 to 1890, 17,999 tons of phosphate of lime and rock were received at British ports and fetched from £2.3.0 to £4.10.0. It is quite possible that the whole of the unenumerated manures and phosphate of lime and rock actually represents Alta Vela phosphate.

DESECHEO

LATITUDE $18^\circ 23' \text{ N.}$, LONGITUDE $67^\circ 29' \text{ W.}$

Shown by Hubbard (1923) as an island about 2 kilometers long and 1 kilometer wide, rising to a height of at least 150 meters in the center. This central hill is heavily wooded (United States Hydrographic Office, 1927a, p. 545). The island appears to be composed largely of Cretaceous shales. There is a Pleistocene or Holocene raised beach deposit (San Juan formation) above the shore line, composed of gravels, formed from rock fragments and shells, cemented together by

¹ Since the above was written, the existence of very fine crystalline material referred to brushite in the Vaux collection of the Academy of Natural Sciences of Philadelphia has come to my attention. The crystals occur on whitish rock, presumably from the terrace.

"guano," presumably phosphatic (Hubbard). The small quantity and mode of occurrence prevent the deposit from being of commercial significance. As has already been indicated, *Sula l. leucogaster*, the brown booby, is common. *S. s. sula* also nests on the island, though presumably in the wooded part above the beach. *Sterna anaetheta melanoptera*, the bridled tern, and *Anous s. stolidus*, the brown noddy, also have breeding colonies on the island (Wetmore, 1918).

MONA

LATITUDE 18° 05' N., LONGITUDE 67° 51' W.

Described by Schmidt (1926) as a block of Tertiary limestone 6.5 miles long and 4 miles wide, with precipitous cliffs, up to 85 meters high, save on the southwest side, where there is a wide terrace 3 to 4 meters above sea level. A smaller islet, Monito, about 400 meters in diameter, lies 3 miles north-northwest of Mona. Primitively the interior plateau of the island was largely forested, but the general appearance suggests great aridity, owing to the porous nature of the limestone. Meteorological data are not available, but according to the "West Indies pilot" (United States Hydrographic Office, 1927a) the rainfall is strictly seasonal, the chief wet season being February to mid-May,

with subsidiary rains from August to mid-October; the intervening months are almost rainless.

The limestone is honeycombed with caves, particularly in the upper parts of the cliffs. Hübener (1898) indicates that the entrances of these caves lie along old strand lines corresponding to various stages in emergence. The caves are warm and damp. Pools of water may be found in them for a large part of the year, and stalactites and stalagmites are well developed. Where light enters a cave, algae grow on the damp surfaces, so that the whole interior is bathed in a beautiful green light. In one smoke-blackened chamber pirates amused themselves by drawing pictures of ships and of their fellows dangling from gibbets.

The phosphate deposits are found on the floors of the caves. Schmidt states that the phosphate is derived from bat droppings; Hughes (1885) describes a similar occurrence in Barbuda. Hübener, however, specifically states that bat guano is limited to a few localities on Mona. His supposition that the phosphate is derived from animal and plant material from which the organic fraction was leached by sea water when the caves lay at sea level is obviously unlikely. Since the inaccessible cliffs of Mona and the whole of Monito are, according to Schmidt, even now

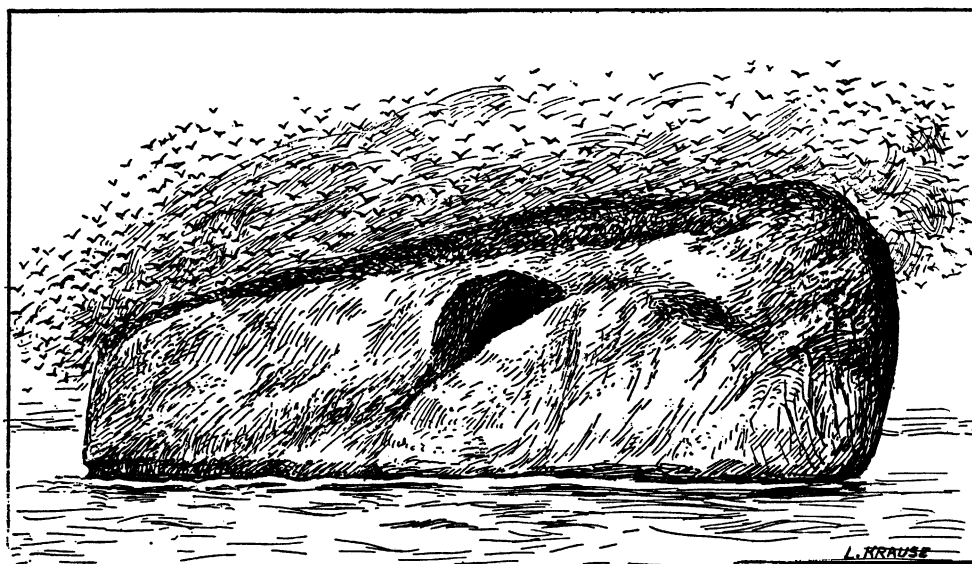


FIG. 75. Monito Island. After Hübener.

colonized by sea birds, it is reasonable to suppose that, whatever the contribution of the bats, that of the birds is also very extensive. Such a conclusion is obviously supported by the sketch of Monito, given by Hübener, and here reproduced (fig. 75). It is, moreover, obvious that unless an abnormally large population of marine chironomids was available, or an abnormally great number of fish-eating bats¹ were present, the phosphate of bat guano cannot have come from the sea. This conclusion in itself makes the avian origin of the Mona phosphate almost certain. Schmidt, and Barnés (1946) give lists of the birds of the islands. *Sula l. leucogaster* was doubtless the most important producer of guano. Barnés noted 87 nests of the species in a large cave called El Toro. *Sula s. sula* is common, and *Fregata magnificens rothschildi* breeds on bushes at the top of the plateau. Colonies of *Anous s. stolidus* occupy inaccessible parts of the cliff, but the noddy formerly bred on the plateau. *Sterna anaetheta melanoptera* and *S. fuscata* also frequent the island. Barnés noted boobies, terns, and the gull *Larus atricilla* Linnaeus flying over large schools of tuna in the channel between Mona and Monito.

From the accounts of both Shepard (1882) and Hübener it is clear that the most striking feature of the phosphates of Mona and of Monito was the quantity of crystalline material present, though brown amorphous phosphate containing organic matter also occurred. Shepard described two new minerals, one being the well-established species monetite, CaHPO_4 , the other, monite, proving on recent examination to be carbonate-hydroxyl-apatite (Strunz, 1939; Frondel, 1943). The crystalline material of the caves of both islands seems to have been largely monetite associated with gypsum. Such minerals presumably were deposited from a guano solution in which the ratio of $\text{CaO}:\text{P}_2\text{O}_5$ was probably less than in the original guano. The hydroxylapatite in part may represent the remaining guano. A mushroom-shaped laminated stalagmite from a cave on these islands was analyzed for Shepard (1882) with the following results:

¹ Mona must not be confused with Monos Island, off Trinidad, where there is a truly remarkable colony of *Noctilio* (Gudger, 1945).

	ANALYSIS BY ROBERTSON	ANALYSIS BY C. W. SHEPARD, JR.
Water, organic, etc.	9.76%	10.91%
CaO	40.27	39.98
(Al,Fe)PO ₄	—	2.90
P ₂ O ₅	40.81 (total)	38.80
SO ₃	6.85	6.80
Insol.	0.58	1.13

As Shepard indicates, the molecular ratio $\text{CaO}:\text{P}_2\text{O}_5$, after correction for gypsum, is 1:0.436. The material is presumably a mixture of monetite and an apatite. A sample of Mona guano, analyzed by Goessman (1892), indicates a more normal phosphatic deposit:

H ₂ O	13.32%
N	0.76
P ₂ O ₅	21.88
CaO	37.49
Insol.	2.45

CAJA DE MUERTOS, PUERTO RICO

The "West Indies pilot" (United States Hydrographic Office, 1927a) describes a Muertos Island as 7.2 kilometers from the coast, 2.4 kilometers long, and of maximum elevation 74.1 meters, situated about 12 kilometers southeast of Ponce. Gile and Carrero (1918) record guano forming a deposit apparently nearly 2 meters (6 feet) thick, northeast of the lighthouse on the cay. They indicate a nitrogen content of from 0.21% to 1.32% N, and a phosphate content of from 14.58% to 33.44% P_2O_5 . Of four samples analyzed, three contained over 31% P_2O_5 . Stutzer (1911) states that the deposit contained 140,000 tons and says, on the authority of Jumeau, that the guano consisted of a loose, light brown, earthy material, containing darker, somewhat more phosphatic lumps.

VIRGIN ISLANDS

Heiden states that phosphatic guano was obtained from the Virgin Islands in the nineteenth century. Though nothing is known of the occurrence, Guano Island, about 1.6 kilometers west of Great Camanoe, would seem to be a reasonable source.

THE LESSER ANTILLES

The Lesser Antilles, or Caribbees, are divided into two series by Davis (1926). The

one-cycle islands, or volcanic Caribbees, form the main arc and are relatively recent volcanic peaks that have undergone a greater or less degree of subsidence. They are surrounded by banks formed from coral reefs leveled at the time of the lowering of the ocean during the Quaternary glaciation. The two-cycle islands, or limestone Caribbees, form a small arc northwest of the main arc, are older and have subsided and then emerged covered with Tertiary limestones. It is probable that the term two-cycle island is misleading in its simplicity, as a number of emergences and submergences have taken place. Biogeochemical phosphatization has occurred on members of both groups. The volcanic Caribbees showing the phenomenon are Redonda, Îlot de la Perle, and possibly other islets off Martinique. The final results of phosphatization are hydrated aluminum ferric phosphates of the general formula $(\text{Al,Fe})\text{PO}_4 \cdot 2\text{H}_2\text{O}$. The limestone Caribbees showing phosphatization are Sombrero, Little Scrub Island off Anguilla (Murchison, 1859), and St. Martins (Voelcker, 1875); to these may be added Bird Island, an isolated islet some distance west of the main arc.

REDONDA

In many ways the most remarkable of the phosphate islands of the West Indies. It is about a mile long and one-quarter of a mile wide and rises to a point 298 meters above sea level. It is surrounded by cliffs, for the most part over 150 meters high. To Davis, Redonda is the central islet of an "almost-atoll," the reef of which has been "cut away and the central islet . . . modified by the waves of the lowered and chilled glacial ocean."

Redonda is frequented by multitudes of sea birds; during the middle of the last century the island was a source of phosphatic guano (Hitchcock, 1891). A trade pamphlet (Wm. Crichton and Son, 1868) quotes analyses by Newland, Buie, and other chemists indicating a normal, partially leached guano. Buie's analysis gave 50% "superphosphate of lime" (presumably actually $\text{Ca}_3\text{P}_2\text{O}_8$), 2% humic acid, 12% undefined animal matter, 17% potassium sulphate, and small amounts of other salts. The rather large amount of potassium implied by the analysis is improbable, and perhaps the whole of Buie's results should be rejected. Newland found 24.67%

organic matter, equivalent to 1.13% N, 6.98% CaHPO_4 , and 43.83% $\text{Ca}_3\text{P}_2\text{O}_8$.

After this phosphatic guano was removed from the island it was found that a phosphatic mineral lay below it. This material was, according to Voelcker (1875), first mistaken for calcium phosphate. Shepard (1869, 1870a) recognized the mineral as hydrated aluminum ferric phosphate, and gave it the name redondite, but its exact nature has never been properly determined, and it may well prove to be barrandite. Hitchcock describes the island as formed of a basalt-like lava, which in the thicker flows shows a concretionary or columnar structure. The phosphate forms a cement between the columnar fragments. There seemed to be two main phosphate-bearing sheets separated by a layer of ash, but Hitchcock implies that wherever there is fragmented lava the phosphatic cementing mineral is present. Tempany (1915) gives a somewhat different account of the occurrence. He states that the island is formed of an andesitic volcanic rock associated with softer beds of compacted volcanic ash, which latter correspond to the Terrass deposits of Montserrat. From the general account of the Caribbean arc given by Schuchert these volcanic rocks may date from any time since the mid-Tertiary. The phosphate veins, according to Tempany, are apparently superficial but can occur in the middle of igneous rock masses in unbroken continuity, "displaying no signs of fissuring or cleavage, which would appear if the material had been formed as the result of solution and subsequent redeposition." The material varies in color from white to red as the content of ferric oxide increases. The material richer in aluminum, described as crust and agate phosphate, was preferred commercially, as the redder varieties, containing more iron, naturally contained less P_2O_5 . The highest P_2O_5 content given in Tempany's analyses, which do not separate the sesquioxides, is, however, referred to a black form. An impure reddish earth full of phosphate grains, containing 10% to 12% P_2O_5 , is also described by Hitchcock and compared to soil covering ledges. It is doubtless the result of subaerial decomposition of the cemented lava. Hitchcock implies that in places the phosphatic cement extended to a depth of at least 12 meters. A short tunnel beneath the most compact ledges of the

TABLE 28

	I	II	III	IV	V	VI	VII	VIII	IX
H ₂ O —	24.00%	17.99%	22.56%	22.00%	20.00%	23.00%	24.20%	24.80%	21.50%
		(free) 2.27							
H ₂ O +		(bound)	0.78						
Organic matter	—	1.41	0.82	—	—	—	—	—	—
Al ₂ O ₃	16.60	15.16	22.12	24.75	21.00	19.50	24.80	13.40	22.20
Fe ₂ O ₃	14.40	18.94	9.83	8.25	11.50	10.50	5.20	16.60	10.50
CaO	0.57	0.08	0.15	—	—	—	—	—	—
MgO	tr.	0.12	0.06	—	—	—	—	—	—
P ₂ O ₅	43.20	38.02	40.05	42.90	38.30	41.00	40.20	38.20	38.50
SiO ₂ and sand	1.60	5.96	2.65	—	—	—	—	—	6.50

I. Redondite (Shepard, 1869).

II. Brown material (Voigt, 1875).

III. Gray material (Voigt, 1875).

IV–VIII. Commercial analyses (Hitchcock, 1897).

IX. Tate (from Stutzer, 1911).

southern part of the island produced an abundant white phosphatic incrustation, presumably aluminum phosphate. Hitchcock could not believe that guano deposits were responsible for so extensive a phosphatization, but Tempany thinks that volcanic magma was intruded under an extensive phosphate bed, probably a guano deposit, which dissolved in the magma and separated as the latter crystallized. If Tempany's interpretation of the relation of the phosphate deposits to the igneous rock of Redonda is correct, and if Davis' interpretation of the geomorphology of the island be accepted, it is clear that the bird colony responsible for the concentration of the phosphate must have existed in the late Tertiary or possible early Pleistocene. The evidence adduced by Tempany is, however, not entirely convincing, and it seems possible that the phosphatization of Redonda was actually due to guano solutions percolating through cracks and could be much later than the formation of the igneous rocks that were phosphatized.

Of a number of available analyses those given in table 28, in which the sesquioxides are separated, indicate the chemical nature of the material.

ÎLOT DE LA PERLE

An isolated bare rock off the northwest coast of Martinique, composed of andesite which, according to Lacroix (1905), is super-

ficially phosphatized. The phosphatic crust is at least 7 to 8 cm. thick. Petrographic examination shows the phenocrysts of plagioclase and hypersthene of the original andesite to be replaced by opal and the ground substance by a phosphatic mineral which proved on analysis to contain 41.2% P₂O₅, 34.2% Al₂O₃, 24.5% H₂O with traces of CaO and MgO. Though referred to redondite by Lacroix, this material seems to be a practically pure aluminum phosphate and will probably prove to be variscite. It is interesting to note that the magnetite of the original rock is said to have been entirely destroyed during alteration, but the fate of the iron is not clear. Lacroix suspected that another small rock, Îlot Diamant, off the south coast of Martinique, which rock has a large bird colony, would exhibit like phosphatization. Later (1911) he received a stalactite-like sample that he referred to redondite, from this locality. It had a concentric structure, part amorphous, part crystalline, and enclosed fragments of dacite and also fossilized plant remains.

SOMBRERO

LATITUDE 18° 36' N., LONGITUDE 63° 28' W.

The most northwestern of the Lesser Antilles, a small islet about 1650 meters (1800 yards) long, and 370 meters (400 yards) wide and of maximum elevation 12.2 meters. It is a limestone island of Davis' two-cycle type.

Julien (1866), who made the first and only extensive geological study of Sombbrero, considered that eight distinct periods of emergence followed by submergence were recorded as variations of the lithology of the limestone of the island. At the time of the sixth emergence, the island was much fractured, and guano accumulated in the fissures formed in the limestone. At the time of the subsequent incomplete submergence, the superficial guano was lost, but phosphatic material remained in the cracks. This process was twice repeated, so that according to

Julien supposed. Extensive exploitation, which by 1872 had proceeded to below sea level (Voelcker, 1875; Spence, 1878), has probably disturbed the original relations so much that a reëxamination would be difficult.

Voelcker states that the phosphate varied considerably in color, most being light yellowish green, but bright green, bright yellow, violet bluish, or pinkish specimens also occurred. The chemical composition varies somewhat, particularly with regard to the quantity of $(\text{Al,Fe})_2\text{O}_3$. Analyses were published by Anderson (1859), Wicke (1859),

TABLE 29

	Voelcker				Range, All Analyses
Moisture	7.51%	10.09%	4.22%	2.94%	2.75%–10.09%
Water of combination, organic matter, etc.	6.19	4.90	6.57	5.94	0.20 – 8.35
P_2O_5	35.09	34.11	34.76	35.52	31.70 –39.64
CaO	38.19	38.42	39.07	37.99	22.69 –51.70
MgO	0.44	0.41	0.52	0.58	tr. – 2.95
Alkalis, F	1.87	1.61	1.85	1.92	0.20 – 1.92
Fe_2O_3	3.22	2.85	2.98	3.70	} 0.96 –19.21
Al_2O_3	4.26	4.23	6.23	7.55	
CO_2	1.36	1.68	1.75	0.96	0.81 – 7.33
SO_3	0.44	0.36	0.36	0.42	tr. – 1.07
Cl	0.39	0.31	0.28	0.43	0.13 – 0.87
Insoluble siliceous matter	1.04	1.03	1.41	2.05	0.47 – 2.05

Julien there were three separate periods of phosphatization. Davis quotes Julien's account at length but appears to be somewhat skeptical of its details. Fossils from the Sombbrero limestone, presumably collected by Julien, were reëxamined by Hubbard (1923) and appear to indicate a middle or lower Miocene age (Schuchert, 1935). No modern study of the land shells said to occur in the phosphate filling of the fissures and to include "*Pupa*" sp., now not known on the island (Julien, 1866), has been made, so that the age of the phosphatization is unknown. Bones, including the remains of giant *Chelonia* said to resemble the well-known tortoises of the Galápagos Islands, apparently occurred in the phosphate (Julien, 1866) and gave the impression that the Sombbrero deposit was a bone breccia. There seems little reason to doubt that most of the phosphate was derived from ancient bird droppings, as

Nesbit (1860), Phipson (1862b), Piggot (Wood and Grant, [1857 or 1858]), Ritthausen (1863), and Voelcker (1860, 1875). Voelcker's four most complete analyses (1860) are given in table 29, together with the ranges for certain constituents. Allowing for calcium combined as CaCO_3 and CaSO_4 the molecular ratio $\text{CaO}:\text{P}_2\text{O}_5$ is 1:0.38, for the mean of Voelcker's four analyses, given above. If it be assumed that all the Al_2O_3 and Fe_2O_3 are present as phosphates, the ratio $\text{CaO}:\text{P}_2\text{O}_5$ for the calcium minerals is 1:0.26. The first value is probably excessive, the second certainly too low. It is reasonable to suppose that some but not all the iron and aluminum were combined as phosphates. Such phosphates must certainly have been present in Anderson's sample containing 19.21% $(\text{Al,Fe})_2\text{O}_3$, 22.69% CaO, and 36.36% P_2O_5 . The mean $(\text{Al,Fe})_2\text{O}_3$ content for all 16 analyses is 8.15%. As in other West Indian

localities, such an amount seems large for an island composed only of coral rock. The bulk of the calcium phosphate was presumably present as an apatite-like mineral, but a partially dehydrated brushite, described by Julien as metabrushite, presumably containing both $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ and CaHPO_4 , occurred on the island. Julien also described as zeugite a mineral subsequently identified by Frondel as whitlockite, $\beta\text{-Ca}_3\text{P}_2\text{O}_8$, but perhaps better termed martinite, as it apparently contains carbonate.

The British trade statistics (Great Britain, Parliamentary Sessional Papers, Trade and Navigation) indicate that from 1852 to 1891, 63,264 tons of "guano," 65,979 tons of "unenumerated manures," and 64,001 tons of "phosphate of lime and rock" were imported from the British West Indies. Most cargoes appear to have realized £4.0.0 to £5.0.0 per ton, the usual price for good phosphatic material. It is probable that much of the aggregate of 193,244 tons came from Sombrero and Redonda. Since Sombrero was worked extensively before 1872, and since the category of "unenumerated manures" does not appear until 1871 and that of "phosphate of lime and rock" until 1882, it is obvious that much material imported in the early years as guano was very low in organic matter and later would have probably been called phosphate of lime.

LITTLE SCRUB ISLAND

A rock 12.2 meters high, off Anguilla, reported to have a deposit of phosphate like that of Sombrero, containing 25.75% P_2O_5 and with nitrogenous organic matter present. The material is said to look like a bone breccia (Murchison, 1859).

ST. MARTINS ISLAND

LATITUDE $18^\circ 04' \text{ N.}$, LONGITUDE $63^\circ 04' \text{ W.}$

Voelcker (1875) gives eight analyses of phosphate from this island, but no data as to the mode of occurrence beyond that the material lay on coral rock. The "West Indies pilot" (United States Hydrographic Office, 1929a) described Guano Cay as a small rocky islet half a mile east of St. Martins, rising abruptly to a height of 30.5 meters and slightly wooded. This islet was presumably a source of St. Martins guano. The mean and

extreme values for the major constituents determined in all specimens are:

	EXTREMES	MEANS
Water	2.26- 5.69%	4.55%
P_2O_5	16.67-36.94	30.42
CaO	40.88-53.48	48.75
CO_2	2.65-20.60	9.56
Insol.	0.20- 4.19	1.68

The sample lowest in phosphate also contained the lowest amount of calcium and the highest amount of insoluble matter, water, and CO_2 . Assuming the latter present as CaCO_3 (46.81%), the remaining calcium oxide would be 14.67%, corresponding to a molecular ratio of $\text{CaO}:\text{P}_2\text{O}_5$ of 1:0.467. There can be little doubt that aluminum or ferric phosphate was present in this impure sample, as 11.97% is given as " $(\text{Al},\text{Fe})_2\text{O}_3$, etc."; this is in harmony with the high water content. Omitting this sample and assuming all CO_2 present as CaCO_3 , the corrected molecular ratio of the mean values of $\text{CaO}:\text{P}_2\text{O}_5$ is 1:0.321, an entirely normal figure. Two of Voelcker's analyses are relatively complete; they refer to a good and to an impure sample containing coral rock:

Water	3.56%	5.04%
P_2O_5	35.13	24.14
CaO	50.41	47.69
MgO	0.22	0.38
SO_3	0.45	0.18
CO_2	6.59	14.20
Fe_2O_3	1.40	1.51
Al_2O_3	1.37	2.99
Insol. (presumably largely SiO_2)	0.87	3.87

BIRD OR AVES ISLAND

LATITUDE $15^\circ 42' \text{ N.}$, LONGITUDE $63^\circ 38' \text{ W.}$

An isolated coral island surrounded by a reef lying to the west of the Caribbean arc. The island is about 1200 meters long, 460 meters wide, and emerges 5.5 meters above sea level. It was listed by Palmer (1900) under the name of Aves Island as a registered United States guano island. There appears to have been a prolonged dispute as to the ownership of the island, the United States, Venezuela, and the Netherlands all having claims. In a letter (Great Britain, Parliamentary Sessional Papers, 1857) dated August 25, 1854, Rear Admiral Arthur Fanshawe

transmits to the Secretary of the Admiralty extracts of an account written by Commander de Horsey who says that 200,000 tons of guano, realizing \$35.00 per ton, were present. A later letter written by Captain Paynter, February 25, 1857, says that the island was frequented by eight men from St. Eustatius Island between January and April. By February 17 they had secured 5000 birds and reckoned to obtain 1000 eggs per day for three months. The birds are said to be two species "of sterna known by the common names of widiawabus¹ and boobies." The guano is described as not pungent like that of the Peruvian and Ichabo deposits. It lay under about 10 inches of sand, lime, and drifted guano on madreporal coral, live rock, and sand. Where guano had been removed a concrete of lime, sand, and salt formed. About one-third of the deposit had been shipped by American workers, whom Captain Paynter considered were engaging in a foolish enterprise. The "West Indies pilot" states that fishermen still visit the island in March and April to collect sea birds' eggs, which are sold in St. Thomas. The vegetation is said to consist of grass about 6 inches high, but there is now no appearance of guano. The only analytical information based on material that can definitely be referred to this island is contained in trade pamphlets (Philadelphia Guano Company, 1856a, 1856b; data in part from Agricultural Report of the United States Patent Office, 1854, p. 95). In these pamphlets guano imported from Bird Island, some 400 miles from the coast of Venezuela, 200 miles south of St. Thomas, and 150 miles westward of Guadalupe, is said to be by far the richest source of phosphate yet discovered. The analysis given by A. A. Hayes is as follows:

H ₂ O	2.40%
Organic and NH ₃ salts	6.20
(Ca, Mg) ₃ P ₂ O ₈	78.80
P ₂ O ₅	11.40
Sand and dirt	1.20

Neglecting the presence of magnesium, this corresponds to 42.70% CaO and 47.50% P₂O₅ or a molecular ratio CaO:P₂O₅ of 1:0.438. It is clear that a considerable amount of CaHPO₄, presumably as monetite, was present in the sample.

¹ *Sic*; obviously a mistranscription of wideawakes.

In addition to this record there are other analyses from localities less certainly to be identified as the Bird Island in latitude 15° 42' N., longitude 63° 38' W. Thus Nesbit gives an analysis of a very different kind of guano from Bird Island, "some distance to the west of St. Vincent." In this analysis 69.61% of the material was gypsum; the remaining material contained:

H ₂ O	26.31%
Organic matter	22.69
SiO ₂	2.80
Fe ₂ O ₃	tr.
Alkaline salts	1.32
MgO	1.41
CaO	26.14
P ₂ O ₅	19.28
N	1.61

The molecular CaO:P₂O₅ ratio is 1:0.287; some carbonate was presumably present. The description of the position of the Bird Island from which Nesbit obtained his material is not in good agreement with Bird Island at latitude 15° 42' N., longitude 63° 38' W., but other small Bird Islands, off Antigua and Grenada, are even less likely to be Nesbit's locality. There is considerable possibility of confusion with the Venezuelan Aves Islands. Three analyses given by Anderson (1858) of Bird Island guano indicate that calcium sulphate (52.42%), calcium carbonate (36.45%), or alkaline earth phosphates (44.15%) are, respectively, the most abundant constituents of the three samples. Nitrogen varied from 0.47% to 1.24% and organic matter from 9.70% to 17.85%. The composition, particularly of the sample highest in CaSO₄, is clearly comparable to that of Nesbit's material containing 69.61% gypsum, and at least part of Anderson's material doubtless came from the same source. If Nesbit's and Anderson's samples came from the same locality as the sample analyzed by Hayes, it is reasonable to suppose that a rather small deposit of highly phosphatic material lay over gypsum and calcium carbonate and that the best part of the deposit had been removed by 1858.

THE VENEZUELAN AND DUTCH LEEWARD ISLANDS

Along the southern margin of the Caribbean is a line of islands belonging structurally

and politically to Venezuela and sometimes termed the Leeward Islands, a term more usually appropriated by writers in English to the northern part of the Lesser Antillean arc. The Venezuelan islands are, according to Schuchert, to be considered as part of the Coast Range of Venezuela and like this range are composed of metamorphosed schists with various igneous rocks of uncertain age. Many of the islands are, however, entirely covered with coral rock. It is probable that virtually all the smaller members of the group originally bore phosphatic guano. The larger islands at the eastern end of the chain, Margarita and Blanquilla, seem to have been destitute of the material. Ernst (1884) states that Orchilla was the first of the Venezuelan islands to be exploited, then El Gran Roque, Los Testigos, and Islas de Aves. It is certain that other islands contained phosphate. To the west lie the three larger Dutch islands of Bonaire, Curaçao, and Aruba, all of which contained phosphatic deposits, but at least in part these were originally deposited on small isolated stacks. On the mainland of the Peninsula of Paraguaná, which is connected to the mainland only by a narrow spit and was no doubt formerly the largest island of the group, some guano has apparently been dug (United States Hydrographic Office, 1929a).

The Venezuelan Leeward Islands are the driest islands fringing the Caribbean. According to Reed (1928) the mean annual precipitation is less than 380 mm. along the central part of the Venezuelan coast, though it rises to 910 mm. at Rio Caribe, about opposite the eastern limit of insular phosphatic deposits, and to 530 mm. at Maracaibo at about the western limit. La Guaira, on about the same longitude as Los Roques, has an annual rainfall of 283 mm., while Coro, at about the same longitude as Aruba, has 281 mm. per annum. The islands may not be quite so dry as the mainland, the mean values available being (Franze *in* Murphy, 1936):

Margarita	245 mm.
Bonaire	440
Curaçao	559
Aruba	438

The mean annual temperature at Maracaibo is 28.6° C., with little seasonal variation; the mean relative humidity is 79%, falling

to a mean minimum of 72% in March (Reed, 1928). In the dry central region most rain falls in the period from June to December. Murphy points out that Lowe's data for Orchilla indicate that breeding of *Sula*, *Fregata*, and *Phaeton* occurs at the close of the rainy season, and that *Sterna fuscata* and *Anous stolidus* breed there in February. Cory likewise indicates *S. l. leucogaster* breeding in January. Terns, other than those mentioned, breed, however, in Aruba in June, and the reproductive season may well be undefined.

THE TESTIGOS ISLANDS

LATITUDE 11° 23' N., LONGITUDE 63° 07' W.

Seven islets and several smaller high rocks* Lowe (1909) says that they are composed of coarse-grained granite (hornblende), overlain in one place by shale. The rocks collected by Lowe were studied by Rutten who found a hornblende granodiorite and a spessartite, close to material from Aruba. Liddle's map indicates Cretaceous sediments. The soil and exposed surfaces of rock are deep ferruginous in the lower parts of the islands. Testigo Grande is richly vegetated, and reaches an altitude of about 183 meters ("West Indies pilot"). The smaller islands have breeding colonies of *Sula l. leucogaster* and smaller numbers of *S. sula*. *Fregata magnificens rothschildi* and a few *Pelecanus occidentalis* (? subspecies = *fuscus* auctt.) also inhabit the group (Lowe, 1909). The only published data on the occurrence of phosphate is an analysis given by Taylor (1857) of a specimen containing 52.07% insoluble siliceous matter. The major remaining constituent was evidently aluminum phosphate and was identified by Taylor as probably variscite.

H ₂ O	12.17%
Al ₂ O ₃	13.03
Fe ₂ O ₃	1.91
CaO	0.37
MgO	0.57
P ₂ O ₅	19.11
SO ₃	tr.
SiO ₂	52.07

BLANCO ISLET

About 2 kilometers northeast of Morro de Punta Moreno, Margarita Island, said in the "West Indies pilot" to have a dark base and

white apex (30.5 meters), probably covered with guano. Margarita Island itself does not seem to have produced phosphatic guano.

LOS FRAYLES

LATITUDE 11° 12' N., LONGITUDE 63° 44' W.

LA SOLA AND LOS HERMANOS

LATITUDE 11° 50' N., LONGITUDE 64° 27' W.

Said in a trade pamphlet (Philadelphia Guano Company, 1856) to have produced Colombian guano. The "West Indies pilot" states that the larger islets of the first-named group are covered with shrubbery and small trees, while the smaller islets are covered with guano. Lowe found all three of the West Indian species of *Sula* (*S. l. leucogaster*, *S. sula*, *S. dactylatra*) nesting on Los Hermanos, *S. l. leucogaster*, though present in great abundance, being outnumbered by *S. sula*. The smaller rocky islets, free of tall plants, would of course not provide a nesting site for the last-named bird. *Fregata magnificens rothschildi* was also common.

Nothing appears to be known of the chemistry of the guano of these islands. Since Spence (1878), who seems to have been deeply interested in the commercial possibilities of the Venezuelan islands, mentions Los Testigos, La Sola, and Los Frayles merely in passing, it is not unlikely that the workings were abandoned on these islands by the time of his visit in 1872, and that the original deposits were small.

CENTINELLA

LATITUDE 10° 50' N., LONGITUDE 66° 05' W.

A rocky islet rising to a height of 21.3 meters and looking like a white sail from the northern side ("West Indies pilot"). Taylor (1857) says the island is inhabited by immense numbers of sea birds. He analyzed several specimens of phosphatic material from Centinella. The first (I) is a sample of fresh guano, from "a little nook in the rocks, where it was protected from the intense dry heat of the sun and from the action of water." The second sample was part of "the concretion which cover the cliffs beneath a bird roost." The third is clearly a phosphatized igneous rock and is said to have consisted of two layers, the upper a dark brown compact

rock, with a partially reniform and enameled surface, the lower apparently paler, but certainly with an exposed surface, and in places much weathered. The lightest portion of the rock was analyzed.

	I	II	III
Ignition loss	53.83%	11.29%	22.87%
CaO	17.99	31.18	2.66
MgO	1.74	1.74	—
Al ₂ O ₃	tr.	1.08	16.24
Fe ₂ O ₃	—	0.78	12.41
P ₂ O ₅	19.50	41.89	31.60
SO ₃	1.98	2.67	1.07
CO ₂	0.40	0.73	—
SiO ₂	2.23	5.97	13.18
Cl	0.12	—	—

In the second analysis, if the MgO, Al₂O₃, and Fe₂O₃ are present as tribasic phosphates and the sulphate and carbonate as calcium salts, the corrected molecular ratio CaO to P₂O₅ is 1:0.55. The analysis is quite likely not very accurate, but it is reasonable to suppose that much of the calcium was here present as monohydrogen phosphate, as Taylor realized. For a phosphate content of 37.77%, after allowing for phosphates of bases other than lime, monetite requires 4.77% water, brushite 14.31%. Both minerals could have been present.

ORCHILLA

LATITUDE 11° 48' N., LONGITUDE 66° 10' W.

Stated in the trade pamphlet of the Philadelphia Guano Company to have yielded Colombian guano. Spence (1878) visited the company's workings in January, 1872, and Rost (1938) indicates that ruins of buildings used prior to 1888 by the company exist on Northeast Key (Cayo El Dorado), the most eastern part of the Orchilla group.

Orchilla consists of a narrow island 13.5 kilometers long in an east-west direction and 3.4 kilometers broad. Islets to the northeast form an irregular atoll-like structure around the Bay of Santa Inez; the largest of these atolls, barely separated from the main island, is Cayo El Dorado or Northeast Key. The greater part of the main island and of Northeast Key is formed of a slightly elevated plateau of supposedly Holocene coral rock. The principal island itself has three main hills of crystalline rocks of some complexity,

rising 100 to 130 meters above sea level (Rost, 1938). Rutten (1931) compares some of the rocks to those of the coastal range and thinks both Cretaceous schists and much older gneissic rocks are present. Rost thinks that the old material is at least of Devonian age.

Spence gives an amusing account of the Philadelphia Guano Company's workings. It appears that the company was permitted, as the result of legislation promulgated in 1871, to exploit guano but not mineral phosphate. The question then arose as to the nature of the material exported, and a commission of nine official members, three being generals, one chemist, and two armed policemen, and three unofficial members, one being an artist, one a musician, statistician, and newspaperman, and one Spence himself, set out to investigate. The manager of the diggings knew no Spanish, and it appears that all dealings with him went through the official interpreter, General Leon van Praag, into more or less classical English, and from him through Spence into American vernacular English. The commission judged, but seemed to have acquitted the manager, though their final question was, "At what date did the birds cease to produce the substance you ship and call guano? To which the victim, after mature deliberation (in a voice of sorrow), replied, 'I do not know.'"

Spence states that Cayo El Dorado rose 6 or 7 meters above low water, as an irregular parallelogram 4 kilometers long and 1.2 kilometers wide. A small amount of vegetation was present, growing on a few inches of sand. When the sand was removed a thin layer of phosphatic guano was disclosed. Spence said that the analyses made by the company ran from 10% to 32% P_2O_5 , the mean being about 22%. Williams gives an imperfect analysis indicating 12.88% moisture, 14.60% organic and volatile matter, and 22.51% P_2O_5 , supposedly as calcium triphosphate. A rather problematic mean analysis published by Goessman (1892) gives as the average of 12 samples 26.77% P_2O_5 with extremes 18.11% to 35.43%; the figures for H_2O 7.31%, CaO 39.95%, MgO 3.29%, SO_3 2.68%, insoluble 1.27%, probably refer to the sample richest in phosphate. The amount exported from 1867 to 1871 seems not to have exceeded 6000 tons, while 12,000 tons

were available ready to ship in 1872. Ernst (1884) says that the total export between 1869 and 1882 had a value of B 1,345,986 and that in 1880-1881, 3987 tons valued at B 294,882 were shipped. Unless great fluctuations in price occurred the amount shipped up to 1882 must have been about 18,200 tons. This estimate makes Spence's figures appear rather high. In 1883 Ernst says that 7986 tons were exported and that at that time the greater part of the material had been removed. Work ceased by 1888. The original reserve thus seems to have been between 30,000 and 40,000 tons.

It is clear that the deposit exploited was not the result of a bird colony that existed up to the time of exploitation, the remark of the manager and more significantly the covering of sand indicating this unequivocally. Spence says, however, that though he saw few birds, they visit the island to breed in April and May. Less pure phosphatic guano existed on the surface of the periphery of the main island.

THE ISLAS DE AVES

Sometimes called Bird Islands in the older literature published in England and the United States. They comprise two groups of islets on separate reefs, the eastern Ave de Barlovento (latitude $11^{\circ} 58' N.$, longitude $67^{\circ} 29' W.$) and the western Ave de Sotavento (latitude $11^{\circ} 58' N.$, longitude $67^{\circ} 43' W.$). The islands have been described by Sievers (1898), who based his account on the diary of R. Ludwig, a German geologist who examined the islands for phosphate deposits in 1883, and by Rost (1938). Rost states that the Aves Islands are typical slightly elevated atolls. The coral rock of the atolls is set on an earlier platform now a little elevated, though scarcely 1 meter above sea level, and on this guano was deposited.

The climate is hot and dry, and the islands are in general barren. Ludwig found a yellow-footed species of booby, no doubt correctly referred to *Sula l. leucogaster* by Lowe, nesting on one of the smaller of the Ave de Barlovento islets, about 64,000 m^2 in area, and characterized them as living guano manufacturers. In the center of the principal islet of the Ave de Sotavento group is a lagoon in which phosphate was deposited, in part

directly and in part by being washed in from the rim of the island. Rost thinks that guano reached the lagoon owing to slight epeirogenetic earth movements which resulted in redeposition of the guano. Birds are numerous; Ludwig speaks of four kinds of herons, duck and other such fowl, and flamingos. The guano on Ave de Barlovento was much mixed with sand, presumably as the result of a great storm in 1877. On Ave de Sotavento accumulation in the lagoon protected the guano from this mixture, and there are said to be alternating layers of guano and plant debris; this was supposed by Ludwig to be due to successive storms, prior to 1877, washing material into the lagoon.

Aikman (1894) states that a sample of Aves Island guano contained 34% P_2O_5 . Two analyses by Guntz (*in* Heiden, 1887) of crude and prepared Aves guano are given below:

	CRUDE (Coarse fraction > 2 mm.)	PREPARED
H ₂ O	4.24%	6.83%
Organic	6.37	7.03 (total N 0.284)
Fe ₂ O ₃	} 0.19	0.22
Al ₂ O ₃		0.36
CaO	45.77	42.62
MgO	2.46	2.03
K ₂ O	n.d.	0.14
Na ₂ O	n.d.	1.44
(NH ₄) ₂ O	n.d.	0.22
P ₂ O ₅	25.18	33.12
SO ₃	n.d.	1.19
CO ₂	14.35	3.84
N ₂ O ₅	n.d.	tr.
Cl	n.d.	1.07
F	n.d.	—
SiO ₂	n.d.	0.18
Sand	0.20	0.17

The prepared material used in superphosphate manufacture probably represents the deposit from which unphosphatized coral, shell fragments, etc., have been sifted. In it the CaO:P₂O₅ ratio, corrected for sulphate and carbonate, is 1:0.343. Fluorine is, according to Heiden, definitely absent. Ernst says that 3.274,292 (*sic*) kilos were exported in 1883 by the firm of Polly, Boom y C^a, all being shipped to Hamburg. No other statistics were available.

Rost found the deposits exhausted but, from remains of the artificially dried yellowish brown material that was available, determined the P₂O₅ content as 24%. The main phosphate was no doubt a carbonate hydroxylapatite, but the Aves Islands are the type locality for brushite, CaHPO₄·2H₂O, which occurred in druses in the phosphate rock.

LOS ROQUES

LATITUDE 11° 57' N., LONGITUDE 66° 41' W.

A group of numerous islets, probably fewer than 100, though reputedly 365 in all. The whole group forms an atoll-like complex, but one islet, Gran Roque, is part of the ancient igneous mass on which the atoll platform was developed. Two-thirds of the island surface, however, is formed of sedimentary rocks, mainly coral fragments mixed with igneous rock debris. The other islands of the group are formed exclusively of coral material. Gran Roque is the only one of the islands that is adequately described and is certainly the most interesting, though the Cayo Grande and Cayo de Aqua are considerably larger. It has been discussed briefly by Spence (1878) and by Sievers (1898) from Ludwig's notes, and more recently by Rost (1938) and by Aguerrevere and López (1938). The last-named authors alone seem to have provided an adequate account.

Gran Roque is 3.15 kilometers long and has a maximum breadth of 0.99 kilometer; the area of the island is 1.755 km². The southern and southeastern parts of the island are flat, consisting of sandy beaches, salt marsh, and lagoons; the northwestern part is elevated, forming a small range of igneous rocks. The climate is certainly arid, rains being rather scarce and of short duration when they occur. The low eastern swamps support mangroves and *Sesuvium portulacastrum* Linnaeus. The drier ground bears only *Opuntia caribaea* Britton and Rose, *O. elatior* Miller, *Cactus caesi* Britton and Rose, and patches of a few square meters of grass. The seas around Los Roques are rich fishing grounds; Gran Roque itself supports a population of about 200, mainly fishermen and their families.

The igneous rocks occupying a third of the area of the island are mainly of basic intrusive type, a medium- to fine-grained diabase

in the eastern and central parts of the elevated section of the island, a coarse gabbro in the west. Dikes of various acid rocks are intruded into the basic massif. Rutten (1931) believes the main rocks of the island to be analogous to late Cretaceous or early Tertiary intrusions in Curaçao, Bonaire, and the Venezuelan mainland. The whole of the elevated parts of the island is covered with a whitish glaze of guano, giving the black rocks a light gray color when seen from a distance. This coating was noted by Spence and also by Aguerrevere and López, who state that it is so thin as to be commercially valueless. Phosphatization of the coral debris of the southeastern part of the island has occurred. Sievers, quoting Ludwig's notes, says that the material was partly powdery phosphate, partly crust, and partly phosphatized coral. Spence, however, was unimpressed by the deposit, and Aguerrevere and López say that the phosphatic caliche, formed by phosphatization of calcareous sands, contains but 5% P_2O_5 . They imply that phosphatic cement occurs in the talus slopes of the hills but do not indicate its chemical nature.

The most important phosphatization on Gran Roque has been produced by accumulation in fractures and cavities in the igneous rock and by the replacement of the gangue material of faults. The latter type of deposit is common on the island, and one occurrence is of commercial importance. This deposit is in a zone of intense shearing in the gabbro of the western part of the island. The zone has been partly filled by a pegmatite dike, which has been largely eroded away, exposing the material of the shear zone to phosphating solutions. The zone is highly permeable to water, springs occur at the bottom, almost at sea level, and salt water used in a drill hole in the phosphate mining operations appeared in the spring. The commercial phosphate vein is about 120 meters long. It is of rather uniform superficial composition throughout, containing 33.20% to 44.30% P_2O_5 in the top 1.5 meters. Deeper, below 10 meters, the phosphate content decreases to below 6.71%. The falling off of the phosphate content clearly indicates a hypogene origin for the phosphorus. The following analysis of a specimen collected at a depth of 1.5 meters is given by Aguerrevere and López:

H ₂ O at 150° C.	5.89%
Loss at red heat	3.14
P ₂ O ₅	44.30
Al ₂ O ₃	21.40
Fe ₂ O ₃	13.65
FeO	0.60
SiO ₂	6.66
TiO ₂	0.23
Cr ₂ O ₃	0.75
CaO	0.40
Na ₂ O	0.64
K ₂ O	2.10

Rost supposed that the action of hot springs on guano was involved and that phosphatization took place in the Tertiary. The account given by Aguerrevere and López indicates that no thermal agency need be postulated, though the date of phosphatization is quite uncertain.

McConnell (1941) has examined material from this locality both microscopically and by X-ray diffraction methods. The phosphatized rock consists in part of secondary quartz granules embedded in a brown cloudy material and in part of a porous material consisting of two kinds of sphaerulites, one with a low birefringence and one isotropic. The isotropic spherulites are probably composed of a material identical with the ground substance in which secondary quartz grains are embedded and which was identified as a carbonate-apatite, the more crystalline part of which was referred to dahllite or possibly lewistonite. The other material, forming the slightly birefringent spherulites, was identified by its X-ray diffraction pattern as barrandite, $(Al,Fe)PO_4 \cdot 2H_2O$. The published analysis, based on a sample which is clearly largely aluminum ferric phosphate, is curiously deficient in water, but in spite of this the Gran Roque phosphate is probably largely to be regarded as barrandite. Clear petrographic evidence of replacement of dahllite by barrandite was obtained from sections.

BONAIRE

LATITUDES 12° 04'–12° 20' N., LONGITUDES
68° 12'–68° 27' W.

The Dutch Leeward Islands consist of three large islands, with associated islets. The easternmost island is Bonaire. It consists of an axis of igneous rocks of Mesozoic age, bearing small patches of Tertiary sediments

and largely surrounded and overlain by Quaternary reef limestones. These latter are particularly extensive at the eastern end of the island. They are undoubtedly of varying age, have been much dissected, and are pitted in places. Small accumulations of phosphatic material in the pockets so formed are found scattered over the surface of these Quaternary limestones, though never in quantity great enough to permit exploitation. Pijpers (1933) states that at a place called Santa Barbara, commercial utilization has been considered but not effected. The Bonaire phosphate has been described by Martin (1879). The individual deposits were very small, reaching a depth of but 16 cm. The material was mainly yellowish brown in color, but reddish or brownish gray and also white varieties existed. It contained numerous cavities, lined or filled with powdery phosphate. Some of the material was markedly banded. All transitions between the phosphate and coral rock occurred. All samples contained carbonate. The specimens richer in phosphate contained from 22.9% to 34.8% P_2O_5 , but they were closely and irregularly associated with material very poor in phosphate. Some of the poorer material contained fossil mollusks. In one phosphate-rich sample, from the southwest of Bocca Oliva, north of Langeberg, about 5 kilometers from the north coast of the island and 40 meters above sea level, fossil teeth and bones occurred. The teeth were identified (Martin, 1879, 1888) as those of sharks, *Oxyrhina* cf. *gomphodon* Müller and Henle, or cf. *glauca* Müller and Henle, and *Carcharodon* aff. *megalodon* Agassiz. Pijpers (1933) thinks that the latter may be derived from Tertiary rocks.

Indeterminate fossils of *Vermetus* and *Perna* were also present. Later Martin (1888) recorded in addition teeth of the ray *Myliobatis* sp. and bones of *Manatus* sp. from material from near Fontein, a locality about 1.5 kilometers from the north coast of Bonaire, and supposed that the phosphate of such occurrences was derived from the bodies of these animals. Hughes (1885) says that he found bones and teeth scattered in all directions "over an area of two miles." This presumably refers to the same or a comparable occurrence, but Pijpers (1933) is skeptical of the record.

LITTLE CURAÇAO

LATITUDE 12° 00' N., LONGITUDE 68° 39' W.

A low, flat, bare islet, having a maximum length of about 2.5 kilometers and a width of about 730 meters (United States Hydrographic Office, 1937b). Its surface is apparently composed of Quaternary limestone on which there was formerly a deposit of phosphatic guano. The deposit consisted of a gray powdery material 1.5 to 2.5 meters thick with some hard nodules in the lower part. The material is said by Meyn (1879), to whom most of the available information about the occurrence is due, to have contained about 31.6% P_2O_5 . The same authority says that about 100,000 tons were estimated to have been present on the island. According to Grutterink (1928) 90,000 tons were actually shipped between 1872 and 1888.

CURAÇAO

The largest of the three Dutch Leeward Islands, this island has a phosphatic deposit of very considerable magnitude. It is unfortunately not so well described as might be desired, commercial considerations having apparently led to restriction of information. Meyn (1879) gives the first important description of Curaçao phosphate, though not from personal experience of the material *in situ*. Martin (1885), the pioneer student of the geology of Curaçao, gives some information but not from personal investigation. Molengraaf (1931), who has recently studied the geology of the island, is virtually silent on the phosphate deposit. The only account that is of any great significance is that of Grutterink (1928) who describes the main phosphate deposit on Curaçao as follows.

The Tafelberg, Santa Barbara, a hill in the southeast part of the island at about latitude 12° 06' N., longitude 68° 51' W., rises to a height of 190 meters above sea level. Its flat top corresponds to an old marine terrace; other younger terraces occur at 105 meters and 25 meters.¹ The phosphate deposit is

¹ Molengraaf (1931) indicates terraces at 150 meters, perhaps at 140 meters, perhaps at 115 to 135 meters, at 90 to 110 meters, 50 to 85 meters, and 20 to 45 meters. Presumably the 150-meter terrace corresponds to the flat summit of the Tafelberg at Santa Barbara, the 90-100-meter terrace to Grutterink's 105-meter terrace

associated with the second terrace. It rests on coral limestone of the Pleistocene Seroe Domai series, which has a very irregular surface. Cone-shaped masses of phosphate penetrate into the limestone, while irregular blocks of limestone project up into the phosphate. This description strongly suggests the Karrenfeld developed on some of the elevated Pacific phosphate islands. The boundary between the limestone and the phosphate is sharp.

may rest directly on limestone or occupy cavities in the phosphate rock. Again the description is reminiscent of Ocean Island or Nauru.

Prior to 1895 about 180,000 metric tons were shipped. After a period when the deposit was not exploited, 444,000 metric tons were shipped between 1913 and 1924. The approximate amount remaining was known but not divulged by the company. It was said to be small compared with the phosphate re-

TABLE 30

	I	II	III	IV	V	VI	VII
H ₂ O "hygroscopic"	7.30%	10.41%	0.64% 0.20	0.68%	1.20%	2.46%	2.47% ^a
H ₂ O "bound"							
Organic							
N	0.35	0.50	—	—	—	—	—
CaO	42.76	35.93	51.00	51.04	51.08	49.50	49.96
MgO	1.73	2.95	0.97	1.26	0.69	1.70	1.23
Al ₂ O ₃	—	—	—	—	—	—	0.40
Fe ₂ O ₃	0.59	0.57	0.20	0.35	0.43	0.45	0.61
TiO ₂	—	—	—	—	—	—	0.024
Na ₂ O	0.87	—	0.11	—	—	1.23	0.88
K ₂ O	—	—	—	—	2.34	0.04	0.09
MnO	—	—	—	—	—	—	< 0.003
Cr ₂ O ₃	—	—	—	—	—	—	< 0.005
V ₂ O ₅	—	—	—	—	—	—	0.01
P ₂ O ₅	35.32	34.70	39.96	40.45	40.62	40.66	38.59
SiO ₂ and insol.	0.56 ^b	1.84	0.33	0.50	0.30	0.50	0.39
CO ₂	2.30	2.22	3.08	3.05	2.92	2.73	3.90
F	—	—	0.48	0.42	0.18	0.38	0.70
Cl	0.53	—	0.12	—	—	0.14	0.16
SO ₃	1.29	1.47	0.63	0.64	—	0.72	0.61

^a A sample containing 38.59% P₂O₅ gave 0.17% organic C and 0.013% N.

^b 0.35% insol.

The phosphate is usually dull but light colored, though sometimes dark brown. It contains cavities of which the walls are often coated with an agate-like phosphate with alternating brownish yellow and pure white layers. Meyn states that the cavities may be lined with calcite or aragonite, or microcrystalline pseudomorph of calcium phosphate after these minerals. Loose, pebbly, and sandy phosphate also occurs, partly covering and partly replacing the solid material. The sand

bearing phosphate, and the 20-45-meter terrace to Grutterink's 25-meter terrace. It is not quite clear if the two doubtful terraces and the 50-85-meter terrace are considered by Molengraaf to be present on the Tafelberg, Santa Barbara.

serves of the world; it may be reasonably presumed that the original reserve was not more than one or two million tons.

Grutterink points out that the original bird colony that produced the phosphate must have occupied the region above the shore at the time of the formation of the second terrace. The position of the bed indicates that the colony was protected from the northeast trade wind by the emergent upper part of the Tafelberg. From the most recent account of the island (Molengraaf, 1931) it appears that, subsequent to the formation of the terrace at about 150 meters, the island emerged in stages until it stood about 30 meters higher than it does today. A subsidence of about 100

meters, indicated by a series of wave-cut notches, then occurred. This event is supposed by Molengraaf to be post-glacial, but the rise in sea level is too great to have been eustatic, determined by the melting of the ice sheets. A subsequent elevation of the island by $65 \pm$ meters occurred. The coral reefs formed marginally after this elevation are now uplifted about 5 meters, forming the Asiento series.

Grutterink's account of the surface of the limestone on which the phosphate rests suggests subaerial dissection prior to, or solution during, phosphate deposition. Perhaps the Pleistocene elevation was as simple as Molengraaf supposes, but it seems quite possible that a more complex series of events took place.

Curaçao phosphate is perhaps better known chemically than any of the other insular phosphates. The most complete analyses (see table 30) are given (I) by Krockner (1873), (II) by Karmrodt (1873), (III) by Güssefeld (*in* Heiden, 1887), (IV and V) by Gilbert (*in* Meyn, 1879), and (VI and VII) by Jacob, Hill, Marshall, and Reynolds (1933). The last analysis is of extraordinary importance as constituting the most complete study ever made of a phosphate of biogeochemical origin.

In addition Voelcker (1866) gives seven analyses. In one of these the water and organic matter are low, 1.34% and 0.84%, respectively. In this sample 37.53% P_2O_5 is present. In the other six samples the water varies from 8.05% to 16.80%, the organic matter from 5.81% to 8.70%, while the phosphate varies between 29.55% and 33.44% P_2O_5 . The phosphate contents of these samples on a water-free and organic-free basis lie between 36.0% and 40.4%, so that they differ from a modern sample such as VII primarily in their higher water and organic content. A specimen similar to Voelcker's wetter samples was also analyzed by Peters (1873). A number of other incomplete analyses are given by Meyn.

In addition to these analyses, Braun (1896) gave a fluorine determination, finding 2.85% F; as in the cases of other phosphate rocks that he analyzed this is doubtless much too high. Jacob, Hill, Marshall, and Reynolds give two other fluorine determinations of

0.75% and 0.91% F. Apart from Braun's determination, which may be rejected, the seven available analyses for fluorine agree in being very low for a rock phosphate; the ratio F: P_2O_5 varies from 0.0044 to 0.0240. The ratio of the mean values is 0.0072, but in the figures of Jacob, Hill, Marshall, and Reynolds, which are probably more accurate than the others, the mean values are 0.685% fluorine and 38.94% P_2O_5 , giving a ratio of 0.0176. Whatever the best value for the ratio, it is strikingly lower than the ratios derived from Angaur, Makatea, Ocean Island, and Nauru phosphates. The iodine content of the two samples submitted to general analysis by Jacob *et al.* was 122 milligrams per kilo in the sample containing 38.59% P_2O_5 and 37.0 milligrams per kilo in the sample containing 40.66% P_2O_5 . These values are higher than those derived from other insular phosphates but are exceeded by some non-insular material. Tremearne and Jacob (1941) determined arsenic in three samples of Curaçao phosphate, finding:

P_2O_5	AS MILLIGRAMS PER KILO
30.31%	12.0
40.66	7.6
38.59	11.8

The last two analyses clearly refer to the same material as was used for the iodine determinations and for analyses VI and VII given in table 30.

The sample containing 38.59% P_2O_5 used for analysis VII was analyzed for copper and zinc by Jacob *et al.*, who obtained 0.045% ZnO and 0.005% CuO.

An interesting feature of the Curaçao phosphate is the occurrence of phosphate as pseudomorphs after gypsum. Martin indicates that gypsum crystals occur commonly at the surface of the Quaternary limestone, and on the Tafelberg the sulphate has been replaced by phosphate. Individual specimens might be up to 10 cm. long. Kloos (1888) thought that this mineral, which he named martinite, had the composition $2Ca_3(PO_4)_2 \cdot 4CaHPO_4 \cdot H_2O$. His analyses are given below as I and II. More recently Hendricks, Hill, Jacob, and Jefferson gave another analysis (III).

	I	II	III
H ₂ O	4.52%	} 5.46%	} 5.43%
Organic	0.75		
CaO	46.78	47.63	44.58
MgO	—	—	3.28
Na ₂ O	—	—	1.86
K ₂ O	—	—	0.62
Fe ₂ O ₃	—	—	0.27
SiO ₂	0.20	—	0.47
	(insol.)		
P ₂ O ₅	47.67	47.87	38.42
CO ₂	—	—	1.54
SO ₃	—	—	0.98

Fluorine was shown by Kloos to be absent. The specimens examined by Hendricks *et al.* and by Frondel (1943) give the X-ray powder pattern of β -Ca₃(PO₄)₂. They differ from typical whitlockite in having slightly lower refractive indices, slightly lower specific gravity, in containing about 4.5% H₂O, and in the presence of CO₂. It is to be noted that the analysis of Hendricks *et al.* differs considerably from that of Kloos for type martinite. It has recently been suggested by Fleischer (1944) that the name martinite be used for carbonate-whitlockite, but it cannot be regarded as certain that Kloos' mineral was identical with that more recently examined.

ARUBA

LATITUDE 12° 24' N., LONGITUDE 69° 52' W.¹

The island of Aruba (Martin, 1888; Westermann, 1931, 1932) consists of igneous rocks, supposedly Mesozoic and early Tertiary, partly covered with limestones which have been denuded to a considerable extent. While a part of the limestones appear to be middle Tertiary, both Martin and Westermann consider that they are mostly of Quaternary age. There appear to be two series of these Quaternary limestones, the lower, later one lying about 10 to 20 meters or less above sea level, the other from 10 to 135 meters above sea level. In some places they merge imperceptibly into each other, but localities are known where a sharp scarp separates them along the 20-meter contour, though this scarp appears to have formed subsequent to the deposition of the more

¹ Bearing of eastern end of island, where the phosphate deposit is situated.

recent limestones. From the occurrence of angular quartz grains in virtually all samples of these limestones it is probable that the highest part of the island was emergent throughout their deposition. The observed dip in the older limestones is probably due to orogenic movements.

There is apparently evidence of wave cutting into the older limestones at a height of 70 meters above sea level, and it is possible that the later high-level period indicated by this cutting may also be represented by the deposition of younger Quaternary limestones. There is evidence of a slight post-Pleistocene emergence which has exposed recent reef rock.

Extensive local phosphatization of the older Quaternary limestones occurred on the extreme eastern headland of Aruba at Seroe Colorado and Seroe Culebra. The first-named locality appears to be an isolated hill, 38 meters high, separated from the mainland by a low-lying depression formerly covered by the sea (Hughes, 1885).

The Aruba phosphate varies from light gray or yellowish color to rust or liver brown. It contains numerous remains of corals and mollusks, the latter mainly fossilized as internal casts. More massive concretions formed in cavities in the original coral rock are not lacking, and the fractured surfaces may disclose banding. A section on Seroe Culebra, described by Martin, is as follows:

Thin bed of limestone
Limestone breccia cemented by phosphate
Phosphate, 3-5 meters thick, rich in manganese in upper part
Kaolin
Quartz diorite

Westermann (1932), apparently writing of the same section, says that "just E. of the top of the Culebra, in an old phosphate working, the phosphate beds dip towards the east and are covered by organic limestone with *Serpulae* . . . which contains at its base rounded-off fragments of the phosphorite; the thickness of this bed is 1-2 m."

It seems certain that the upper limestone was formed during renewed submergence subsequent to phosphatization.

The paleontology of the locality presents difficulties (Schepman *in* Martin; Vaughan,

1901, 1919; Rutten, 1931; Westermann, 1932). Oligocene corals are apparently present in the phosphate deposit, as well as mollusks known from the Pleistocene and Recent. There were also vertebrate bones, identified as belonging to *Manatus* sp. Westermann seems convinced that attribution of a Quaternary date is correct in spite of Vaughan's determinations of the corals. It is by no means clear what fossils are derived from prephosphatic limestone and what may have been introduced during phosphatization.

Several analyses of the best commercial material have been published (table 31).

oxide. No analysis of manganiferous material was published.

LOS MONGES

LATITUDE 12° 30' N., LONGITUDE 70° 55' W.

Three groups of small islets near the entrance to the Gulf of Maracaibo. Since the only specific statement as to the source of phosphate (Shepard, 1856) indicates that it came from one of a group of five islets, it seems certain that the locality was one of Los Monges del Norte, at the position given above, as Los Monges del Sur consists of but

TABLE 31

	I	II	III	IV	V
H ₂ O + 100° C.	2.06%	5.27%	3.30%	3.65%	3.00%
CaO	49.20	47.62	50.40	47.48	46.36
MgO	—	0.30	—	—	—
Al ₂ O ₃	} 3.72	{ 1.64	} 3.05	3.35	4.80
Fe ₂ O ₃					
P ₂ O ₅	37.28	35.77	36.52	36.13	35.18
CO ₂	2.00	1.89	2.20	2.40	2.50
SO ₃	—	1.74	—	—	—
F	—	2.86	—	—	—
Insol. SiO ₂	2.50	1.33	1.15	2.20	3.15
Alk. organic loss, indet.	3.24	0.78	3.38	4.79	5.01

I is given by Hughes (1885); II is an original analysis by Martin; the other three (III, IV, and V) were derived by Martin from Messrs. Isaac and Samuel, Ltd., of London, who imported Aruba phosphate.

All apparently refer to material dried at 100° C. Martin expressly states that his material lost 3.54% water during the process of drying at this temperature.

These figures do not give an entirely fair picture of the composition. Much phosphate from Seroe Culebra contained about 34% P₂O₅, and there was a complete gradation from true phosphate rock to calcium carbonate not containing phosphate.

All material from the Seroe Culebra contained sesquioxides, up to 9.74% (Al,Fe)₂O₃ being recorded. The surface of the Seroe Colorado deposit in places showed small particles of a green earthy iron phosphate with brown ironstone and black manganese

two islets and the third, Monge del Este, is a single rock.

Shepard obtained his information from Capt. A. F. Winslow, captain of the "Jane Dolen," a vessel that was forced by a storm into the port of Charleston, South Carolina, in 1856, laden with phosphate from Los Monges. According to this authority the phosphatic island was 400 feet high, but the "West Indies pilot" gives the maximum altitude of the northern group as 135 feet, or 41 meters, and the altitude of one islet of the southern pair as 230 feet, or 70 meters. Shepard states the phosphatic island had an area of 200 acres, or about 0.8 km²; the largest or southeasternmost islet of Los Monges del Norte was probably the source of the phosphate.

Shepard indicates that the islet was composed of coralline, Tertiary and trap rock. The last-named material was later char-

acterized as an igneous rock composed mainly of a dark green pyroxenic mineral. According to Rutten (1931) no modern description of the rocks of Los Monges exists.

Shepard indicates that almost the whole island was covered with a layer "many inches" thick of what was termed petrified guano. This material was well known to be richer in phosphate than most natural deposits of calcium phosphate, and was sold under the misleading name of natural superphosphate. As far as can be ascertained from contemporary accounts (Piggot, 1857; Higgins and Bickell, 1857) the deposit was not homogeneous. An outer hard crust evidently covered an earthy deposit, and the latter was richer in phosphate than the former. Thus Higgins and Bickell give:

	CAO	P ₂ O ₅	MOLECULAR RATIO
External hard layer	41.76%	39.92%	1:0.376
Body of rock	39.92	43.50	1:0.439

Similarly Piggot gives, after allowing a little calcium as calcium sulphate and a little phosphorus as ferric phosphate, for the body of rock:

CAO	P ₂ O ₅	MOLECULAR RATIO
35.95%	46.22%	1:0.506

For a sample described merely as guano rock from Monk's Island, allowing for CaSO₄, Taylor obtained:

CAO	P ₂ O ₅	MOLECULAR RATIO
36.54%	42.98%	1:0.454

In this last case a small amount of magnesium phosphate may have been present. It is, however, clear that the material exported from Los Monges consisted largely of less basic phosphates than hydroxylapatite.

The mineralogy of such material was investigated by Shepard (1856); the resulting confusion has recently been dispelled by Frondel (1943). Captain Winslow of the "Jane Dolen," who provided Shepard with his material, believed the phosphate to be derived from guano fused during the extrusion of igneous rock. The minerals of the phosphate rock of Los Monges were therefore termed by Shepard pyroguanite minerals.

The bulk of the material was supposed to consist of two species, pyroclasite and glaubapatite. The latter species, a supposed sodium calcium sulfato-phosphate, was later withdrawn (Shepard, 1882), and at the same time doubts as to the homogeneity of pyroclasite were expressed, Shepard correctly suspecting that it might be a mixture of monetite and monite, i.e., apatite. No type material of either pyroclasite or glaubapatite now appears to exist. A non-type specimen "labelled glaubapatite and answering the original description" from the Canfield collection of the United States National Museum was examined by Frondel. It is not stated explicitly that the specimen came from Los Monges, but this is implied in Frondel's discussion of monetite. The specimen was found to consist of botryoidal monetite with white, earthy whitlockite overlying massive banded apatite and limestone. A specimen of pyroclasite from Jarvis Island, West Indies (*sic!*), found by Frondel to be apatite, is irrelevant to the discussion. Shepard described a third mineral from the locality which he called epiglaubite. It was said to occur "as aggregates, or interleaved masses of minute semi-transparent crystals" implanted on druses of the glaubapatite. No analysis was given. Frondel, following Dana (1892), suspects that this may have been brushite. No type material appears to exist; a non-type specimen from Los Monges, obviously not conforming to the original description, proved to be fine-grained dolomite (Frondel, 1943).

In addition to the determinations reported above some analytical data relating to the Los Monges phosphate are available. Thus Nesbit (1860) gives three analyses in which the phosphate is apparently correctly assumed to be present as monetite:

H ₂ O	1.00%	1.00%	0.40%
Organic	7.90	3.52	3.82
CaHPO ₄	78.67	80.75	76.19
CaSO ₄ ·2H ₂ O, etc.	11.28	11.33	19.01
(Al,Fe) ₂ O ₃	—	1.00	—
Alk. salts	0.35	0.95	0.50
SiO ₂	0.80	1.45	0.10
N	0.14	0.21	0.14

The following analyses are (I) from Morfit (1855) and (II) from Voelcker (1860):

	I	II
H ₂ O	7.10%	2.39%
Organic, NH ₃ salts	2.72	7.93 (org. + comb. H ₂ O)
CaO	40.61	39.48
MgO	2.83	1.17
Na ₂ O	—	—
K ₂ O	tr.	—
Fe ₂ O ₃	0.49	—
P ₂ O ₅	43.28	41.34
SO ₃	3.23	4.57
Cl	0.06	—
SiO ₂	0.49	2.28
N	0.03	0.139

Allowing the MgO as Mg₃P₂O₈ and the SO₃ as CaSO₄, these analyses give values for the molecular ratios CaO:P₂O₅ of 1:0.411 and 1:0.408, respectively, presumably corresponding to a mixture of apatite and monetite. In the first specimen, in which the water content is high, some brushite may have been present. Piggot (1857) gives another analysis in which 35.95% CaO is taken to combine with 46.22% P₂O₅ and 5.78% H₂O; this material, like the materials studied by Nesbit, was probably mainly monetite. Morfit states that 0.16% soluble P₂O₅ was present, but this finding is probably of no significance in view of the difficulty in determining the solubility of such minerals. A specimen analyzed by Anderson (1855) contained 75.69% alkaline earth phosphate with 0.78% soluble P₂O₅; the nature of this specimen is obscure. It is evident, from Shepard's original account, that some fluorine was present in the so-called pyroclastic.

Considering all the available data it seems probable that the Los Monges phosphate consisted largely of monetite mixed with apatite. Where the phosphate rested on reef limestone, which in places may have been dolomitized, it seems probable that an underlying layer of apatite also developed. Martinite or carbonate-whitlockite was certainly present, and brushite may have also occurred. The lower phosphate content of the outer layer may have been due either to apatite or to whitlockite. The former seems more probable, as the whitlockite from the locality is described as earthy, whereas the crust was evidently a hard coherent material. It is most

unfortunate that so little is known of this extraordinary deposit, which probably found its closest analogue in some of the deposits on the islands of the Gulf of California, such as San Pedro Martir and the Farallon de San Ignacio (pp. 131-132).

CHRONOLOGICAL ASPECTS OF THE GUANO DEPOSITS OF THE CARIBBEAN AND CAYMAN SEAS

In view of the lack of information about many of the localities, it is difficult to present the data that are available in definite categories. It has seemed, therefore, best first to list the localities that have been discussed above, with such information that may bear on the chronology of their deposits. The term "contemporary phosphatization" is used to imply that phosphatization was occurring when exploitation began.

Old Providence. No information
Vivorilla Cays and Caxones. Apparently not contemporary phosphatization
Swan Islands. Phosphatization at least mainly not contemporary
Cayman Islands. Phosphate certainly ancient on Karrenfeld on Pleistocene or older limestones
Serrana Cays, etc. Some phosphatization apparently still occurring
Pedro Cays. Some phosphatization apparently still occurring
Bahama Islands and Cuba. No information
Morant Cays. Not contemporary
Navassa. Certainly ancient in pockets of Karrenfeld at two levels
Alta Vela. Contemporary bird colony, but aluminum phosphate perhaps ancient
Desecheo. San Juan formation, Pleistocene or post-Pleistocene, but not contemporary
Mona and Monito. Large bird colony on Monito, but the general impression given by the accounts is that most material is ancient
Puerto Rico. No information
Virgin Islands. No information
Redonda. Superficial phosphatic guano apparently contemporary. Aluminum phosphate may be Pleistocene or even older
Perle. Probably not contemporary
Diamant. Probably contemporary
Sombbrero. Certainly ancient, presumably Pleistocene or older
Little Scrub Island. Probably not contemporary
St. Martins Island. No adequate information
Bird Island. Apparently contemporary

Testigos Island. No information
 Blanco Island. Apparently contemporary
 Los Frayles. Apparently contemporary
 La Sola. Apparently contemporary
 Los Hermanos. Apparently contemporary
 Centinella. Contemporary phosphatization
 Orchilla. Not contemporary
 Ave de Barlovento. Contemporary
 Ave de Sotavento. ?Contemporary
 Los Roques. A little contemporary guano;
 aluminum phosphate ancient, but time of
 formation unknown
 Bonaire. Probably Pleistocene
 Little Curaçao. No information
 Curaçao. Apparently Pleistocene
 Aruba. Apparently Pleistocene
 Los Monges. Apparently not contemporary

The localities that appear to have had colonies of birds actually producing guano in the last 150 years are the Serrana Cays, the Pedro Cays, Monito, Bird Island, and five or six of the Venezuelan Leeward Islands. Some modern guano probably coated the old aluminum phosphate on Alta Vela and Redonda. In all at most half of the islands or groups of islands for which any information exists seem to have had large enough bird colonies for contemporary deposition to have occurred, but in many cases the amount of phosphate produced was very small. Except

for the Aves Islands and Bird Island it is doubtful if any of the commercially significant deposits were of recent date. Even where there was a veneer of guano over a massive quantity of aluminum phosphate, the latter may be of considerable antiquity and the modern guano a quite late addition produced by birds that had nothing to do with those producing the main phosphatization.

The deposits of the Cayman and Swan Islands, Desecheo, Sombrero, Navassa, Bonaire, Curaçao, and Aruba, which collectively must have greatly exceeded those produced on the islands with bird colonies still in existence in the nineteenth century, all may be Pleistocene, though at least in the case of Desecheo a Holocene date is possible. The aluminum phosphate on Alta Vela, Redonda, and Gran Roque may well belong with the massive deposits on some of the limestone islands. While, without detailed correlation of the Pleistocene and post-Pleistocene deposits on all these islands, it is impossible to arrive at any definite conclusion, the general impression left by the available data is that more intense phosphatization occurred throughout the region at some past and probably Pleistocene time than was taking place at the time of the arrival of European man.

PHOSPHATIZED LOCALITIES ALONG THE NORTHEAST COAST OF SOUTH AMERICA AND IN THE ADJACENT OCEAN

St. Paul's Rocks and Rata Island of the Fernando de Noronha group are apparently still the sites of active guano production. Two localities or groups of localities, at which considerable phosphatization of primary rocks has occurred in the past, lie on the northeastern coast of South America. Since this region is very much wetter than either the Caribbean or the Brazilian islands farther south, it is therefore conveniently considered in a separate section.

OCEANOGRAPHY

St. Paul's Rocks and the Fernando de Noronha group lie in a part of the Atlantic which may be enriched by upwelling in the Equatorial Counter Current and which

seems to have a richer avifauna than most of the tropical part of this ocean. The Southern Equatorial Current flows along the whole of the coast of northeastern South America, but the littoral waters are strongly modified by the discharge of the Orinoco and the Amazon. Though Hentschel (1935) records many birds off the mouth of the Amazon, Murphy indicates that the great turbidity of much of the inshore part of the Atlantic in this region has a very adverse effect on the avifauna, most of the ordinary oceanic species being absent from British Guiana. Farther east, off French Guiana, there appears to be clearer water, the influence of the Orinoco not reaching so far east or the Amazon so far west (Heilprin, 1906). It is

in this region that the third locality to be discussed below, namely, Grand Connétable, is situated. Little seems to be known about the oceanographic conditions farther east, off the coast of Maranhão, where the second group of phosphatized localities lies.

CLIMATOLOGY

The mean rainfall at Cayenne, very close to Grand Connétable, is 2800 mm. per annum. Precipitation is strikingly seasonal, over three-quarters of the fall occurring in the first six months of the year, and September being almost rainless. From French Guiana moving southeast along the coast of Brazil the rainfall declines slightly, being 2442 mm. at Para and probably somewhat less on the Maranhão coast where the second group of phosphatized localities is found. Out to sea, and a little north of these localities, the rainfall is lower, slightly less than 1300 mm. per annum at Fernando de Noronha and presumably not very different at St. Paul's Rocks.

DESCRIPTION OF THE ISLANDS WITH CONTEMPORARY BIRD COLONIES

ST. PAUL'S ROCKS

LATITUDE 00° 56' N., LONGITUDE 29° 22' W.

A group of five large rocks over 50 meters in diameter and several smaller rocks. The whole group has a maximum diameter of about 350 meters. Booby Hill, the second rock from the north, is 19 meters high; the other large rocks are from 6 to 18 meters high. The material of which the group is composed consists of a dense, compact dunite, 74% of which is very fresh olivine. The rock shows signs of metamorphism by pressure (Renard, 1882; Washington, 1929) and locally is altered to serpentine. (Pl. 15, fig. 2.)

Murphy has considered all the available ornithological data, concluding that the avifauna consists of *Sula l. leucogaster*, *Anous s. stolidus*, and *A. minutus atlanticus* Mathews. The first-named species occupies the upper parts of the islets. The noddies appear to nest lower on the rocks, *A. s. stolidus* here constructing no nest, while *A. m. atlanticus* makes a bracket-like nest of seaweed and guano against a sloping or vertical rock surface. It is probable that the greater part

of the guano of St. Paul's Rocks is derived from the booby colony.

Darwin says that from a distance the rocks appear brilliantly white, and the "Sailing directions for South America" indicates that at times they resemble sails. The white coloration is due partly to "the dung of a vast multitude of sea-fowl, and partly to a coating of a hard, glossy substance with a pearly lustre, which is intimately united to the surface of the rocks" (Darwin, 1845). In addition to these substances there is a good deal of phosphate filling cracks in the dunite and producing the impression of dikes of intrusive material.

The amount of more or less unaltered excrement is not recorded; it doubtless varies from season to season according to the raininess of the times or the amount of spray from storms.

The glaze is described by Darwin as consisting of numerous exceedingly fine lamellae, the whole forming a layer of total thickness about 2.5 mm. ("the tenth of an inch"). A small amount of the same material was found by Renard (1882) on rock samples collected by the Challenger expedition. He gives the following analysis, based on but 17.5 milligrams: CaO 50.51%, P₂O₅ 33.61%, traces FeO, MgO, and SO₃. Darwin noted that the material does not effervesce in acid. It is unfortunate that subsequent expeditions do not seem to have paid attention to this material. The nature of the lamellations, which conceivably may represent annual varving dependent on wet and dry seasons, requires further attention.

The phosphatic veins, filling cracks in the dunite, have been remarked by all scientific visitors to St. Paul's Rocks, but the only good account of the material is by Washington. The presence of this phosphate is certainly due to rain and spray washing guano down from the upper part of the rock. Washington particularly examined such phosphate from a vein on Northeast Islet. He describes the material as "dull rusty and earthy looking, with a very rough feel, and easily scratched by a knife. The colors are mostly in dull, light yellow, and some of the specimens are banded with darker streaks."

Thin sections show a transparent, almost isotropic, substance, which appears in the

main colorless, though there are yellowish patches. The texture is mainly spherulitic; scattered through the material are opaque black and slightly translucent brown spots, with very irregular patches of an unidentified colorless birefringent mineral, with a slightly higher refractive index. Some of the spherules have a slightly more refractive outer layer. Analysis gives:

P ₂ O ₅	35.75%
CaO	56.47
MgO	0.30
SiO ₂	0.01
H ₂ O +	3.91
H ₂ O	0.53
CO ₂	3.36
SO ₃	0.36

In addition to Washington's analysis there are three analyses by Renard. The first refers to a "more or less impure phosphate" forming a breccia in a fissure in the dunite, the second to a very peculiar breccia containing shell and bone fragments, and separated from the igneous rock by a thin layer of a black manganese-containing material. It is unfortunate that there are no indications of the site or extent of this bone breccia or of the nature of the bones that it contains. The third analysis is of mammillated, honey-combed mass of phosphate.

	I	II	III
H ₂ O (loss at 110° C.)	4.40%	4.90%	5.23%
Ca ₃ P ₂ O ₈	82.65	38.40	70.46
CaCO ₃	4.86	33.38	6.54
CaSO ₄	4.76	2.90	4.88
MgCO ₃	1.41	—	—
MgO	—	9.37	1.71
Fe ₂ O ₃	1.42	1.45	8.47
FeO	tr.	tr.	—
Mn ₂ O ₃	tr.	0.50	—
SiO ₂	—	7.70	1.41
Insol.	0.50	1.40	1.30

Nothing is said about fluorine in these analyses. It seems improbable that the leading rock analyst of the day should not have examined a phosphate for this element, yet Washington definitely concludes that the material is a dahllite, but one with more hydroxyl than carbon dioxide, replacing the fluorine and chlorine of apatite. The X-ray diffraction pattern was identical with fluorapatite.

If fluorine was really absent, the material is very remarkable. It is probable that in this locality sea spray is continually coming in contact with the phosphate and replacement of OH by F would be expected. In view of the curious differences in fluorine content of various insular apatites and the importance of any climatological or chronological hypotheses framed to explain such differences, it is a matter of regret that no specific information on the St. Paul's Rocks material is available.

RATA ISLAND

LATITUDE 3° 49' S., LONGITUDE 32° 23' E.

The northernmost island of the Fernando de Noronha group, a cluster of volcanic islands, 356 kilometers from the Brazilian coast. The group as a whole has been well described by Murphy (1936). The main island is richly vegetated, originally being covered with a very thick forest. The temperature is very constant, the mean monthly value varying from 25.0° C. in June to September to 26.1° C. in January to May, with extremes of 20.6° and 30.6° C. The mean annual rainfall is 1294 mm., but individual years have had precipitation varying from 460 mm. to 2396 mm. The wet season is from February to mid-July, most rain falling in April and May. The islands have a limited terrestrial fauna; three birds, the endemic *Zenaida auriculata noronha*, *Elainea ridleyana*, and the Brazilian *Vireosylva gracilirostris*, and an endemic legless lizard, *Amphisbaena ridleyi*, are mentioned by Murphy. The sea birds have been listed by the same authority. Both tropic birds and all three tropicopolitan boobies, *Fregata magnificens*, *Sterna fuscata*, *Anous stolidus*, *A. minutus*, and *Gygis alba*, are recorded. Murphy says that *S. leucogaster*, *S. dactylatra*, *Sterna fuscata*, and *Anous stolidus* nest primarily on the outlying islands among which Rata is clearly included. The main mass of the island is phonolite, but Leonardos (1945) says that there is a covering of coral limestone. Much alteration of this material and the igneous rock as well has taken place, so that the resultant phosphate is rich in both calcium and sesquioxides, as is shown by the following analyses (I, II) from Leonardos, (III) from Bovet (1883), and (IV) from Costa Sena (1883):

	I	II	III	IV
H ₂ O organic	13.87%	10.99%	12.00%	12.74%
CaO	28.48	32.08	33.00	39.60
Na ₂ O	—	0.51	—	—
Fe ₂ O ₃	13.04	7.42	} 17.60	} 10.80
Al ₂ O ₃	10.37	9.44		
P ₂ O ₅	26.74	28.03	25.80	21.30
CO ₂	1.10	3.30	1.70	2.16
Insol.	6.40	7.86	10.70	12.00

GRAND CONNÉTABLE

LATITUDE 4° 50' N., LONGITUDE 51° 53' E.

The larger of two barren rocky islets off the approaches to Cayenne, French Guiana. It has an altitude of 50 meters above sea level, while the associated Petit Connétable emerges but 1 meter above the high-tide mark (United States Hydrographic Office, 1927d). It appears from the old accounts of Barrère (1743) and Waterton (1839) that the island was a bird colony, having a considerable population of *Sula*, *Fregata*, and *Phaeton*. There is apparently little or no modern information relating to the ornithology of the region.

Grand Connétable has a considerable deposit of aluminum phosphate which has evidently been produced by the action of guano solutions on the underlying rocks, said by Lacroix (1906) to be gneiss and diabase. According to Andouard (1894) the phosphate is reddish yellow or deep brick red, porous, light, and seemingly amorphous. The following analyses are given, (I) by Andouard (1894), and (II) by Jacob, Hill, Marshall, and Reynolds (1933), recomputed to include water of crystallization given off at 105° C.

	I	II
H ₂ O at 105° C.	21.24%	22.58%
H ₂ O at red heat	2.50	1.64
CaO	1.40	0.00
MgO	tr.	0.25
Na ₂ O	—	0.07
K ₂ O	—	0.06
Al ₂ O ₃	25.59	30.14
Fe ₂ O ₃	8.03	3.62
Cr ₂ O ₃	—	0.014
TiO ₂	—	0.13
ZnO	—	0.031
CuO	—	0.008
MnO	—	<0.003
P ₂ O ₅	39.10	44.50
V ₂ O ₅	—	0.004
SO ₃	0.06	0.08

CO ₂	tr.	0.00
SiO ₂	1.70	1.49
Cl	tr.	tr.
F	—	0.05

In addition Tremearne and Jacob (1941) record 30.5 milligrams per kilo arsenic in what is apparently the same sample as that used for analysis II.

The following analysis is given by Carnot (1896, Carnot *in* Gautier, 1894) of reddish concretionary phosphate from "L'Îlot du Commandeur, situé en face de la côte de la Guyane":

H ₂ O and organic	24.00%
CaO	0.80
MgO	0.15
Al ₂ O ₃	28.60
Fe ₂ O ₃	9.00
P ₂ O ₅	34.88
Clay	2.00

It would seem from Gautier's notice of the occurrence that there was some doubt about the exact locality. Since no Îlot du Commandeur seems to exist on the Guiana coast it is probable that the material came from Grand Connétable.

ANCIENT PHOSPHATIZATION ON THE
COAST OF MARANHÃO

The northern coast of the state of Maranhão west of Vizeu consists of a low-lying littoral belt with mangroves fringing higher ground. Within this coastal belt the land rises and is composed of pre-Cambrian igneous rocks. The coast is interrupted by mouths of many small rivers, which form deep, wide estuaries in drowned valleys. The account of the region by Froes Abreu (1939) indicates post-Pliocene submergence and planation followed by a slight emergence, though a more complex history is not improbable. Isolated areas, apparently primitive bosses of diabase, have resisted planation. The surface of the diabase has become deeply altered to laterite or

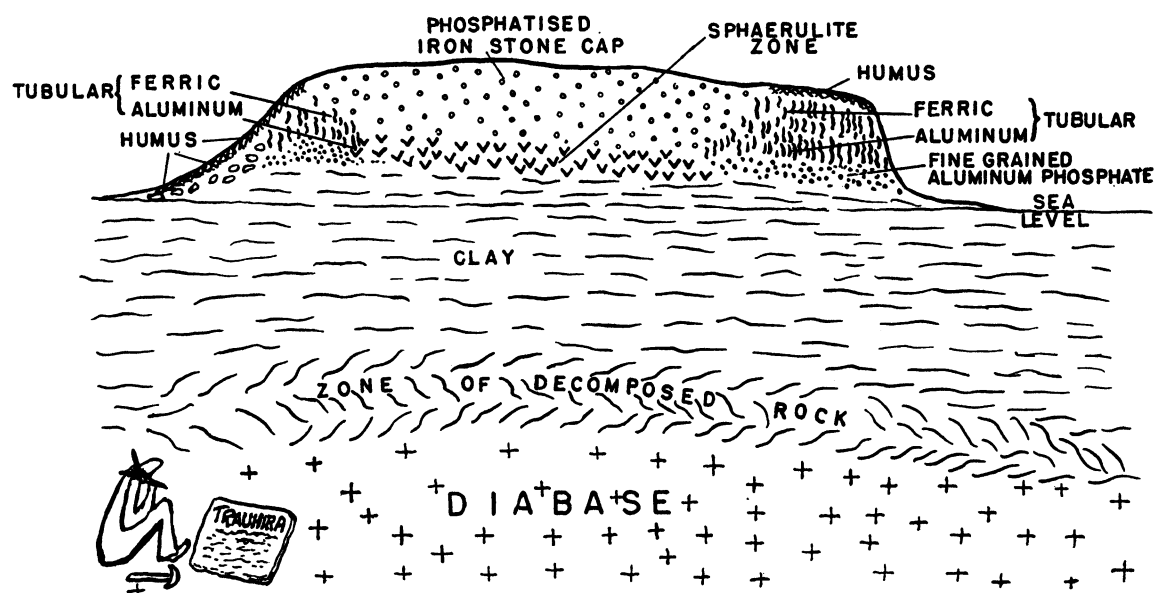


FIG. 76. Section showing phosphatization at Trauhira. After Brandt.

bauxite. Such low hills evidently formed islands at the time of maximum submergence and became sites of bird colonies. Phosphatic alteration of the laterite has taken place on at least two such hills, namely, Piracaua, some little distance inland from the coast, and Trauhira, set in a mangrove swamp at about sea level. A brief account of the region by Shaw, Wright, and Darnell (1925) suggests that other similar localities exist. The whole region is auriferous; placer deposits have been worked around the foot of Piracaua. Trauhira alone has been adequately described.

TRAUHIRA

LATITUDE $1^{\circ} 25' S.$, LONGITUDE $45^{\circ} 30' W.$

A small hill about 20 meters high, rising out of a mangrove swamp at about sea level. The hill presumably represents an ancient island. The structure of the deposits (fig. 76) has been discussed exhaustively by Brandt (1932).

The central plateau of the hill is shown in Froes Abreu's photograph as having a grass cover, below which there is evidently a cap of ironstone covered with very little soil; peripherally there is a ring of humus on the slope from the plateau to the sea, and in places this humus extends onto the extreme edge of the plateau. Borings through the central

part of the plateau disclose:

5-8 m.	More or less phosphatized ironstone
1-2	Zone of crystalline sphaerulites
40-50	Clay
Varying thickness	Zone of decomposed rock
Bed rock	Diorite

The ironstone cap in section is found to be very heterogeneous. It consists of reddish concretions of partly phosphatized ferric oxide of varying degrees of hydration, and green concretions of dufrenite (kraurite) cemented together by a solid aluminum phosphate gel. In most cases the concretions show signs of alteration at their surfaces, which are covered by a layer of yellow ferric hydroxide. Within this layer and below in the layer of sphaerulites an aluminum phosphate mineral is found, which apparently represents the product of crystallization of the aluminum phosphate gel. This material apparently in part replaces hydrated ferric oxide concretions and in part forms octahedra replacing a crystalline mineral, possibly pyrite. The aluminum phosphate mineral of the loose sphaerulites and octahedra is described as harbortite, and is supposed to be a basic aluminum phosphate of composition $6 Al_2O_3 \cdot 4 P_2O_5 \cdot 17 H_2O$, differing from wavel-

TABLE 32

	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	CaO	Na ₂ O	P ₂ O ₅	H ₂ O
Ironstone cap (crude)	0.6%	1.6%	15.1%	48.3%	0	1.0%	1.1%	19.5%	12.9%
Brown, hard concretion of ironstone cap	0.3	1.1	5.1	68.0	—	1.1	0.3	14.9	9.0
Violet brown concretion of ironstone cap	17.6	1.3	15.4	53.5	—	0.1	0.6	1.2	9.1
Yellow white weathering product of iron concretion from surface below humus	2.0	2.6	28.1	9.3	—	5.1	3.8	31.1	17.7
Dufrenite from ironstone cap	0.6	0.2	1.5	52.8	—	0.9	1.2	32.0	10.6
White harbortite, octahedral pseudomorph from ironstone cap (Mol. ratio: H ₂ O:Al ₂ O ₃ :Fe ₂ O ₃ = 4.15:1.29:0.11)	0.6	1.3	32.7	4.5	—	1.6	4.7	35.4	18.6
Yellowish harbortite, octahedral pseudomorph from ironstone cap (Mol. ratio: H ₂ O:Al ₂ O ₃ :Fe ₂ O ₃ = 4.53:1.34:0.43)	1.7	1.6	28.9	14.4	—	0.7	3.4	30.1	17.3
White harbortite, loose sphaerulite layer (Mol. ratio: H ₂ O:Al ₂ O ₃ :Fe ₂ O ₃ = 4.00:1.31:0.10)	2.8	1.0	33.4	3.8	—	1.2	3.7	35.7	18.0
Brownish harbortite, loose sphaerulite layer (Mol. ratio: H ₂ O:Al ₂ O ₃ :Fe ₂ O ₃ = 4.41:1.28:0.37)	0.3	0.8	29.6	13.3	—	1.5	4.0	32.2	18.0
Tubular structures, upper end	1.8	1.2	8.1	69.0	0	2.0	0.2	6.3	11.2
Tubular structures, lower end, with fine-grained aluminum phosphate	3.7	1.6	27.4	13.0	0	6.9	1.6	24.9	19.5
Marginal detritus	6.6	1.3	31.5	7.3	0	2.6	4.4	28.2	17.8
Amorphous concretions of marginal detritus	0.4	1.8	31.9	3.3	—	10.6	2.9	29.7	17.5
Underlying clay boring 1a, SiO ₂ as allophane 19%, kaolin 71%, quartz 10%	32.4	1.1	26.5	23.5	0	0.8	0.2	2.3	13.0
Underlying clay boring 1b, SiO ₂ as allophane 14%, kaolin 43%, quartz 43%	49.4	1.0	23.1	12.1	0	0.7	0.2	2.1	10.4
Decomposed bed rock, marginal boring, K ₂ O 0.3%, SiO ₂ as allophane 36%, kaolin 21%, quartz 43%	52.7	1.0	15.8	8.8	0	4.8	0.9	0.6	11.1

lite in its lower degree of hydration. The analyses of both the octahedral pseudomorphs from the ironstone cap and the sphaerulitic material from below are in close agreement with this formula if small amounts of SiO₂, TiO₂, CaO, and Na₂O be deducted and if in the browner varieties some Fe₂O₃ replaces the Al₂O₃. As is pointed out below, it is not un-

likely that Na₂O is an essential constituent. Potash and magnesia are said to be virtually absent from all the alteration products of the island. The zone of loose sphaerulites of harbortite, apparently cemented with aluminum phosphate gel and containing concretions of dufrenite, is succeeded by a thick layer of clay, apparently all below sea level, which

contains little phosphate. This material is secondarily enriched in silica, partly as quartz, SiO_2 having migrated downwards, leaving the iron at the surface, while alumina behaved in a somewhat intermediate way, as is common in lateritic profiles.

At the sides of the hill, under the marginal zone of humus, the profile is different. The iron cap is replaced by a curious layer of tubular structures like irregular organ pipes. These are composed of ferric hydroxide and aluminum phosphates, the upper ends of the tubes being richest in iron, the lower ends in aluminum and phosphate. Beneath this layer in the marginal zone the sphaerulitic bed of harbortite is replaced by a fine-grained aluminum phosphate.

The outer layers of the tubes are solid; the spaces between them at the top are filled with ferric hydroxide. Internally septae separate the cavities into a series of druses containing granular, lamellar, or cellular material. Brandt states that the main partitions correspond to the aluminum phosphate cement and the finer structures filling the druses to the weathered remains of dufrenite and ferric oxide concretions of the upper layers. No detailed analyses of the different parts of the system are given. Brandt supposes that variations in the ground-water level and the presence of organic matter from the humus layer in this ground water have produced the structures observed, but the exact mechanism is not clear from his account.

Marginally there is a zone of debris from which the iron has been dissolved. Weathering of this material has produced a substance having the appearance of calcareous sinter. Two sorts of sphaerulites are present; one of the same crystalline nature as is found in the central part of the deposit, another amorphous type in which about 10% CaO is present. This calcium is supposed to be derived from the shells of mollusks. Brandt says that even on the iron cap there are accumulations of lamellibranch shells, while in and below the humus remains of shell

beaches occur. Water that has passed through the humus layer is believed to have dissolved such shells and then passed into the zone of marginal debris, dissolving dufrenite and iron oxide and depositing calcium.

Typical analyses of some of the materials from this remarkable occurrence are given in table 32.

Brandt gives, in all, 11 analyses of selected harbortite, which show an Na_2O content of 3.4% to 4.7%; an unsorted sample contains 2.0% Na_2O . Similar analyses for the loose sphaerulite layer give 3.5% and 2.7% Na_2O , while the overlying ironstone gives 1.1% Na_2O and 0.7% Na_2O , and the underlying clay 0.2% Na_2O and 0.7% Na_2O , respectively. It is clear that sodium tends to concentrate in the harbortite, and may be an essential constituent, though this is not discussed.

Brandt describes certain crater-like depressions on the central plateau of Trauhira, which might be regarded as ancient thermal springs that could have been responsible for the phosphatization. He concludes, however, that there is no evidence from the chemical structure of the deposit of such localized sources of phosphate. He believes the depressions in question are due to chemical erosion and comparable to similar structures in other tropical regions. The most reasonable explanation of the deposit is that a lateritized island was covered with guano. Brandt says that large bird colonies depositing guano occur on islets in the region, but gives no details.

His account is very detailed, but it is unfortunate that it takes virtually no account of chronological aspects of the problem. The statement implying complete emergence during the life span of a recent molluscan fauna is vague. The mineralogy of the locality needs further study, particularly in view of the possible presence of sodium as an essential constituent of harbortite. An X-ray diffraction study of the new mineral was made, but its publication, promised by Brandt, seems not to have occurred.

PHOSPHATIZED ISLANDS OFF THE CENTRAL EASTERN COAST OF SOUTH AMERICA

There are a few guano islands off that part of the coast washed by the Brazil Current, between latitudes 17° S. and 25° S.

Hentschel indicates a region of somewhat greater plankton production, along the coast between latitudes 12° S. and 23° S. than is found farther south or farther north. This region, which he calls the Abrolhos region, is attributed to the existence of a shallow shelf. Deep water enriched in nutrients is probably deflected upward onto this shelf which forms a barrier in the deep-water circulation along the South American coast. No indication of an extensive bird population in the Abrolhos region is given by Hentschel.

As far as can be ascertained, the Abrolhos Islands are likely to differ little climatically from the Fernando de Noronha group. The islands off Rio de Janeiro are certainly rather drier, and though the most southern islands lie off part of the coast that is somewhat wetter than is Rio de Janeiro they seem to be drier and more barren than the mainland. None of the localities to be described is likely to have a mean annual precipitation in excess of 1500 mm. per year.

ABROLHOS ISLANDS

LATITUDE 17° 58' S., LONGITUDE 38° 42' W.

A group of five small islands of basaltic lava, apparently overlying Cretaceous sediments and surrounded by reef rock. They were visited by Darwin (1844) who noted the large quantity of bird droppings, and have been described in some detail by Hartt (1870). The largest and highest island is Santa Barbara with a maximum length of 1.2 kilometers and an altitude of 40 meters. Redonda, the chief phosphatic island, is smaller and but 21 meters high. The islands are said to be the resort of innumerable sea birds, though Murphy states that but a single specimen, of *Sula dactylatra*, is known to him from the locality. Hartt records *Fregata* and *Phaeton* and two birds known locally as *piloto* and *beneditos*, as well as gulls. It has not been possible to ascertain the identity of the *piloto* and *beneditos*. Hartt maintains that an islet off Santa Barbara is frequented by frigate birds *in extremis*, and that on the death

of the birds the corpses in various stages of decomposition pile up, contributing to the guano deposit. All the islands are described as having a spectral look, owing to the white bird droppings deposited on them. No true guano layer was observed on Santa Barbara, however, though guano and phosphate occurred in crevices in the rock, and a brownish incrustation, supposedly derived from the leaching of bird droppings, was noted forming patches on the rocks. At the top of the cliff on the eastern side of Redonda, Hartt found a thick bed of yellowish or whitish material, apparently an aluminum phosphate formed by the interaction of guano solutions and material derived from the underlying rock. Darwin indicates an aberrant material on trap rock on one of the islands which he believed was derived from guano and which is doubtless comparable in composition to that described by Hartt. Leonardos indicates that Southeast Island also bears phosphatic material. He quotes Sr. Antônio Martons Andrade of the Guano Brasil Ltda. as estimating the deposits at about 50,000 tons, containing 9.17% P_2O_5 and 0.91% N.

ILHA ANCORA

LATITUDE 22° 04' S., LONGITUDE 41° 05' W.

Mentioned by Leonardos (1945) as the source of a poor phosphatic guano. The "Sailing directions for South America" (United States Hydrographic Office, 1935) indicates a pair of Ancora islands just north of Cape Frio, with a white rock, Gravata Islet, connected with the inner islet by a reef. This rock may be the source of the guano. The Guano Brasil Ltda. estimates the amount present to be 100,000 tons; analysis gave 9.174% P_2O_5 and 0.910% N.

ILHA CAGARRA

LATITUDE 23° 02' S., LONGITUDE 43° 11' W.

South of Cape Frio, one of a group of islands off the entrance to Rio de Janeiro, said by Leonardos, on the authority of the Guano Brasil Ltda., to have about 10,000 tons of inferior phosphatic guano, containing 5.489% P_2O_5 and 0.672% N.

ALCATRAZES ISLANDS

LATITUDE 24° 06' S., LONGITUDE 45° 41' W.

Described by the "Sailing directions" as a group of barren islands. The highest island is 268 meters high. They are said by Knecht to be composed of porphyritic granite with hornblende. In places on the south side, yellow aluminum phosphate mixed with small quartz grains occurs (Knecht, 1940). Analysis gives:

H ₂ O (ign. loss)	16.20%
SiO ₂	39.80
Al ₂ O ₃	19.14
Fe ₂ O ₃	1.86
P ₂ O ₅	27.98

Murphy indicates that *Sula leucogaster* appears to inhabit islets in the vicinity and suspects that the name of the Alcatrazes Islets refers to this bird. The "Sailing direc-

tions" give the English name Cormorant Islands as an alternative.

CASTILHO ISLAND

LATITUDE 25° 14' S., LONGITUDE 48° 08' W.

Said by the "Sailing directions" to be a nearly barren islet about 10 meters high, apparently more arid than the preceding locality. Leonardos (1945) indicates an estimated 20,000 tons of material containing:

H ₂ O	8.840%
Comb. H ₂ O + org.	12.686
P ₂ O ₅	12.310
N	0.714

The nature of this material is obviously uncertain. Leonardos indicates that smaller, poorer deposits exist on other islands still farther south along the coast of the state of São Paulo.

ISLANDS OF THE TEMPERATE SOUTH ATLANTIC AND OFF PATAGONIA

The final localities to be considered lie in the Temperate region off the south of South America. The current in this region is the Falkland Current, which arises as a branch of the west wind drift and flows northward up the coast of South America. The entire Atlantic south of latitude 30° S. appears to be more productive than is the central southern Atlantic and undoubtedly supports a richer avifauna (Hentschel, 1936). This productivity increases southward. The maximum density of the ocean bird population appears to be at about latitude 50° S., or about the latitude of the localities to be considered below. In general the productivity of the Falkland Current region is greater than that of the regions at like latitudes farther east. It must, however, not be forgotten that farther north extensive bird colonies exist on Gough Island and the Tristan da Cunha group. On these islands the conditions are doubtless similar to those found on the Subantarctic Islands of New Zealand. Little or no discrete deposition of guano appears to take place, but the presence of birds bringing nitrogen compounds and phosphate from the sea to the land must have influenced the biota of the islands considerably. Wilkins (1923) writing of Gough Island, where the precipitation is probably in excess of 1650 mm. per annum,

writes of "rank vegetation growing in the rich guano soil." An alleged guano deposit on the north side of Nightingale Island (I) proved not to contain phosphate, but small quantities of P₂O₅ are recorded (II) from a cave deposit on Middle Island of the Nightingale group (Douglas, 1930).

	I	II
H ₂ O	72.12%	17.00%
Organic matter and NH ₄		
salts	24.70	15.15
P ₂ O ₅	0	3.85
CaO	0	5.10
MgO, alkalis	1.60	10.20
Siliceous matter	1.58	48.70

The first sample can hardly be of fecal origin; the second presumably contains some guano mixed with inorganic mud or sand.

The deposits of the Patagonian islands and the Falkland Islands were evidently much greater than these doubtful accumulations.

THE PATAGONIAN DEPOSITS

According to Arancibo (1938) four localities in Magallanes have guaneras. Some of these localities may be on the western coast off the South American mainland, but are most reasonably associated with the other better known Patagonian deposits. Diego Ramirez

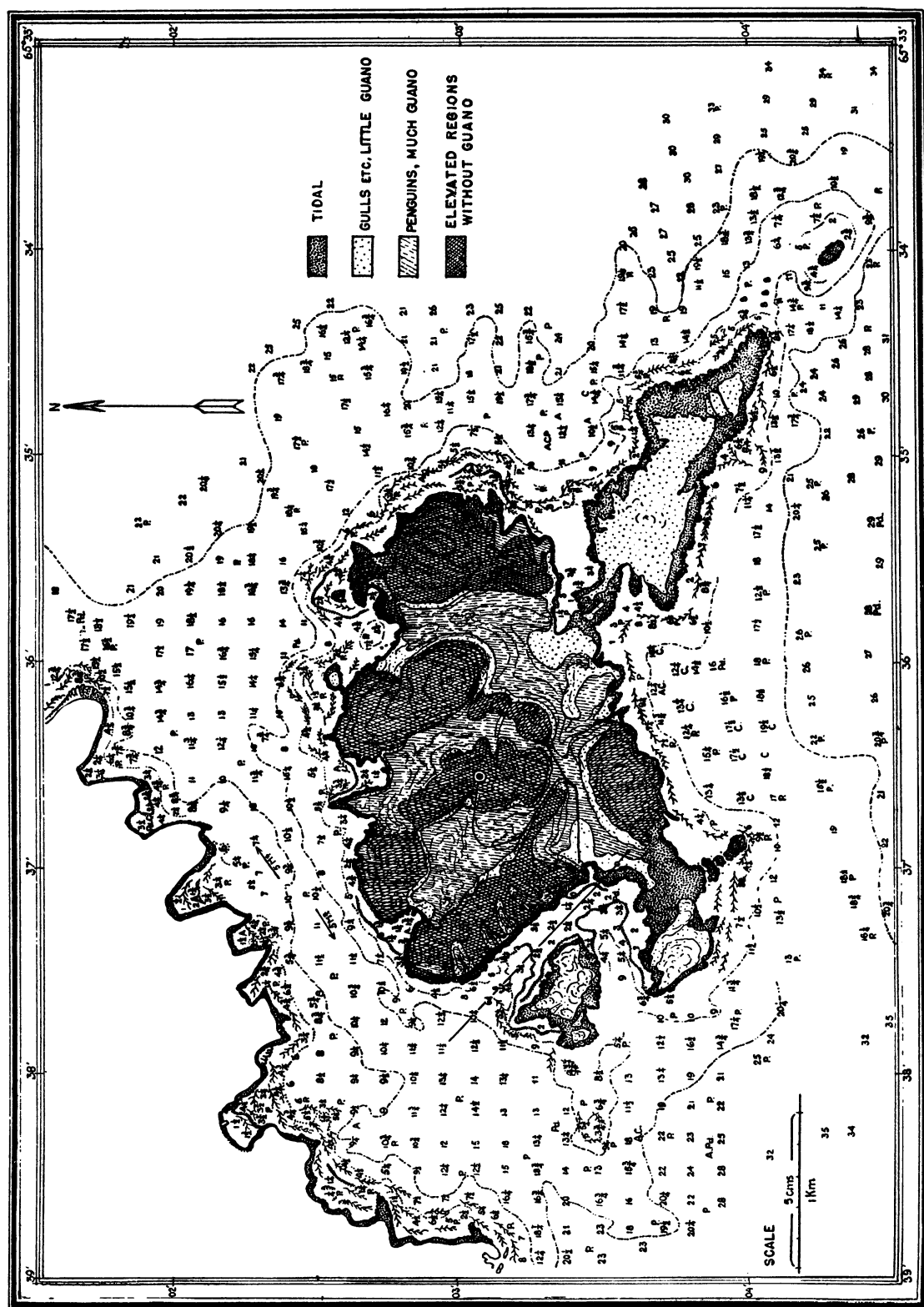


FIG. 77. Isla Leones. After Catalano.

and Staten Island are indicated as phosphatic guano islands by Holzschneider (1937), while off the mainland of the Argentine, Penguin Island and Leones Island have significant deposits. Murphy says that British vessels began to load shortly after 1840 and that the traffic continued at least until 1885. The Penguin Islands were the most important source but "many other islets, as far north as the Rio Negro were examined and scraped clean." The climate of this region is somewhat diversified (Murphy, 1936). Staten Island has an annual precipitation of 610 mm.; Leones and Penguin Islands are drier, the wet western winds being cut off by the Cordillera. The rainfall on Leones is known to have varied in two successive years from 303 to 89 mm., and the range may be considerably more extensive. Diego Ramirez must, on the other hand, be much wetter. The most important deposits were certainly those of the drier islands. It is possible that the low mean and maximum temperatures may have played a slight part in reducing the solubility and the rate of decomposition of the guano. In general, however, the immense penguin colonies of the Antarctic islands do not seem to accumulate guano, so that low temperature in itself is not effective in permitting a deposit to develop in the face of high precipitation and run off. Specific accounts of only three, albeit the most important, localities have been published.

ISLA LEONES

LATITUDE 45° 03' S., LONGITUDE 65° 36½' W.

An irregular, rocky island about 1 kilometer from the coast. Omitting outlying islets separated only at high tide, it is about 2 kilometers wide and just under 3 kilometers long and rises to an altitude of over 90 meters in the center. The main mass of rock is a quartz porphyry. The principal guano deposits occupy the lower areas between several rocky bosses, and small valleys cut into the coastal cliffs. Catalano (1933) states that the material is due exclusively to the penguins, undoubtedly *Spheniscus magellanicus* (Forster), that nest in such places. He indicates on his map certain less productive areas, largely on the outlying, partially separated islets to the south, that are said to have little guano and to be inhabited by "gaviotas y

patos." Catalano's map (fig. 77) is instructive if the general type of distribution is compared with the distributions recorded by Brügger around the now elevated islands of the north Chilean coast. The general pattern, both of accumulation in small valleys and in more extensive mantles between the elevated parts of the island, is similar in the two cases, but very different from the lenticular masses that formerly crowned the pampas of the Chinchá and Guañape Islands.

A number of partial analyses of guano from Isla Leones are given by Catalano. A profile from one of the more important deposits, 2 meters thick, gave:

CENTIMETERS	P ₂ O ₅	N	INSOLUBLE IN ACID
0-50	3.82%	0.59%	76.64%
50-100	4.11	1.15	61.70
100-150	6.36	0.82	63.47
150-200	12.63	0.83	54.14

Six other samples from depths of 50 cm. to 250 cm. in old workings were also analyzed; the mean and ranges for the 10 samples are:

P ₂ O ₅	N	INSOLUBLE IN ACID
3.82-12.63%	0.58-1.37%	13.50-76.64%
7.90	0.84	47.53

Whitish concretions apparently formed by phosphatization of decomposed igneous rock are evidently common on Leones. Catalano indicates that they consist of a potassium aluminophosphate, rather than hydrated aluminum phosphate as is found in the Caribbean and other tropical regions. Analysis gave:

H ₂ O	31.71%
Al ₂ O ₃	20.67
Fe ₂ O ₃	0.86
K ₂ O	7.98
(NH ₄) ₂ O	present
Na ₂ O	2.64
CaO	sl. tr.
MgO	tr.
P ₂ O ₅	32.47
Insol.	3.67

The material is presumably taranakite, discussed in greater detail below. Leones guano was also examined by Anderson (1857) who found 13.58% P₂O₅ and 42.7% organic matter and ammonium salts; 29.95% was gypsum, etc. This older material was evident-

ly much freer from inorganic material than are the modern samples.

PENGUIN ISLANDS

LATITUDE 47° 54' S., LONGITUDE 65° 43' W.

These and the adjacent rocks off Puerto Deseado were apparently the most important sources in the nineteenth century. The old accounts of the vast numbers of *S. magellanicus* present in the region have been collected by Murphy. The main island of the group is 1.1 kilometers long and is formed of two main masses with a central flat area between them. Wichmann indicates that the guano is deposited in this region in undulations between the rocks, the depth reaching 20 cm. The adjacent Isla Chata is said to have a partial covering up to 50 cm. thick (Wichmann, 1933). Prior to the nineteenth century exploitation, the maximum depth was undoubtedly greater than Wichmann's figures indicate.

Sea-lion guano apparently from this locality was found by Malaguti (1861) to consist of bones, skin, fish scales, and crystalline

globular masses of an aluminum phosphate (P_2O_5 32%) probably identical with that described by Catalano from Leones and doubtless referable to taranakite.

An old guano, called "guano de carrière," covered with gravel to a depth of 1 meter, was also found on the islands and examined by Malaguti. It contained large pyramidal crystals of struvite (De la Provostaye, 1861) and in general resembled the more recent penguin guano, save in it the nitrogen content was only 1% to 3% N. Goessman (1885) gives an analysis which indicates the composition of such old, largely phosphatic material:

H_2O	12.10%
N total	0.73
N·NH ₃	0.26
N·NO ₃	0.24
P_2O_5	24.35 (0.35% soluble, 6.97% "reverted")
K_2O	0.14

Two profiles are given by Catalano. As on Leones there is an indication of enrichment of phosphate in the lower layers:

	1		2			
	0	0.5 m.	0	0.5 m.	1 m.	2 m.
P_2O_5	3.01%	10.39%	2.89%	5.36%	6.82%	13.64%
N·NH ₃ *	0.23	2.49	—	—	—	—
Acid insol.	45.80	2.44	25.26	33.44	67.84	48.53

* Catalano and Wichmann record NH₃ rather than total nitrogen. The ammonia here is converted to nitrogen, but some other nitrogen was doubtless also present.

material, both as single crystals (I) and as crystalline masses (II) whose composition he gave as:

	I	II
Organic	23.50%	23.24%
CaHPO ₄	22.10	10.20
Ca ₃ P ₂ O ₈	51.30	56.76
CaSO ₄	—	5.87
CaF ₂	1.90	0.70
SiO ₂ sand	0.20	3.00

The crystals are supposedly a mixed phosphate forming pseudomorphs after gypsum. It is unfortunate that the analysis gives no water content. Struvite also occurred.

The guano referred to the penguin colony contained 4% to 4.35% N and lacked both oxalate and uric acid.¹ It contained numerous

Wichmann also gives the first two analyses and quotes a third very low in ammonia nitrogen (0.028%) and with 4.27% P_2O_5 . He also collected material from the surface of the deposit near the landing place, which contained:

H_2O at 105° C.	7.28%
H_2O + volatile, organic, etc.	16.89
N·NH ₃	0.017
Fe ₂ O ₃	4.76
Al ₂ O ₃	19.65
P_2O_5	9.95

It is obviously impossible to form any clear idea of the nature of this deposit.

SHAG ISLAND

Adjacent to the last two localities, is said by Malaguti (1861) to have a great cormorant colony and to have produced guano which contained feathers, bone fragments,

¹ Barral (1875), however, indicates 6.09% and 7.89% N in Panguia Is. (*sic*) material.

and rare crystals of carbonate (*sic*) of ammonia, presumably, teschemacherite. The nitrogen content varied from 8% to 12%, about a third of the material consisted of calcium triphosphate, and small quantities of oxalate, nitrate, and chloride were present.¹

UNSPECIFIED PATAGONIAN LOCALITIES

An analysis from the east coast of Patagonia by Grimm, recorded by Ullmann (1906), is based on material from latitude 49° S., longitude 67° 50' W. The composition is as follows:

H ₂ O	16.15%
Ign. loss	28.06
N	4.40
CaO	20.20
(Al,Fe) ₂ O ₃	0.99
P ₂ O ₅	15.43

A large number of analyses of Patagonian guano were published during the nineteenth century, without precise indication of the source. Ure and Teschemacher give a mean of 14 analyses:

H ₂ O	25.1%
Organic and NH ₃ salts	18.9
N	2.09
(CaMg) ₃ P ₂ O ₈	44.6
Sand	5.0

Nesbit gives 10 analyses of Patagonian guanos, though these may include some samples from the Falkland Islands. There is an obvious numerical error in one analysis (11.19% Ca₃P₂O₈ for 21.19%), which has been rectified in presenting the summary below:

	RANGE	MEAN	LEAST-CONTAMINATED SAMPLE
H ₂ O	3.40–30.68%	15.48	30.68%
Org.	12.73–32.45	19.27	19.93
N	0.56–4.89	1.87	3.60
SiO ₂	10.20–40.83	28.22	10.20
(Al,Fe) ₂ O ₃	0.00–6.36	3.32	0.85
CaO	2.95–16.09	9.50	16.09
Alk. salts	0.00–9.70	4.38	3.15
P ₂ O ₅	5.73–14.46	9.56	14.46
Mg, CaCO ₃	0.00–4.64	0.92	4.64
CaSO ₄ , 2H ₂ O, etc.	0.00–29.14	8.79	—

At least one sample, reported as containing 5.48% Ca₃P₂O₈ and 12.73% (Fe,Al)PO₄ must

¹ In a paragraph overlooked until the above was written, Domeyko (1874) mentions Magallanes guano from

have contained ferric or aluminum phosphate in some form. Three other samples are said to have 1.70% to 3.70% of such phosphates, but the attribution is clearly an analytical convention and need not be valid.

Voelcker (1876) gives four less complete analyses in which the nitrogen varies from 0.62% to 1.83% with a mean value of 1.13%, and the phosphate, given as (CaMg)₃P₂O₈, from 7.6% to 12.7% P₂O₅, with a mean value of 10.0%, on the assumption that magnesium was present in negligible quantities.

The original reserve present in the Patagonian guaneras can never have been great, but the aggregate quantity imported into Great Britain between 1846 and 1863 was 84,360 tons, of which 38,181 tons arrived in the first-named year. The annual mean price during the period 1859–1863 varied from £2.15.0 to £6.10.0, in reasonable agreement with the analyses already given.

THE FALKLAND ISLANDS DEPOSITS

Deposits of guano, doubtless comparable to those of Patagonia, were exploited in the Falkland Islands. St. Johnston (1920) notes that export of guano from New Island (latitude 51° 40' S., longitude 61° 16' W.), a small island in the extreme western part of the group, was undertaken under government license as early as 1851. The first cargo reaching Great Britain was received in 1853, in which year 178 tons were imported (Great Britain, Parliamentary Sessional Papers, 1854). The total amount of guano originally present in the group was evidently small.

	RANGE	MEAN	LEAST-CONTAMINATED SAMPLE
Quartermaster Island and Santa Magdalena Island, containing 17.3% P ₂ O ₅ and 1.5% to 2.0% N. There have been confusions about the names of some islands. Shag Island is probably the Shay Island of Heiden, and might even be Shaw's Island of Voelcker (p. 190).			

By 1867, the last year during the nineteenth century in which there were imports into Great Britain, the total quantity received was but 2317 tons. This suggests much less important deposits than occurred on the drier Patagonian islands.

An anonymous article (Anon., 1914) describes penguin guano from Cochon Island and Kidney Island, at the extreme eastern end of the group, in the entrance to Berkeley Sound (latitude 51° 35' S., longitude 57° 42' W.) as consisting of black, wet, slimy masses containing much organic matter with some fibrous material. A few small bones of birds, a small quantity of sand, and, in one sample from Kidney Island, about 7% of fine gravel were present. Analyses of these samples are given in table 33. Little otherwise seems known as to the localities or modes of occurrence of the guano.

The available climatological data for the islands relate primarily to the eastern part of the group (Brooks, 1920). At Cape Pembroke (latitude 51° 41' S., longitude 57° 42' W.) the mean January temperature is 9.6° C., the mean July temperature 2.6° C. The diurnal variation is small, and hot days are very rare; on only about four days in the year may a maximum of over 17° C. be expected. Minimum temperatures below 0° C. may be expected on just over 40 days per year. The precipitation at Stanley in east Falkland is about 640 mm. per year, and the

mean relative humidity at Cape Pembroke 84%. The western parts of the group doubtless have a higher rainfall.

Such guano as accumulates under these rather unfavorable climatic conditions is doubtless mainly produced by penguins. The commonest species is *Eudyptes crestatus* (J. F. Miller), the rock hopper, though *S. magellanicus* and the gentoo or Johnny penguin, *Pygoscelis papua* (Forster), are also common in the group (Murphy, 1936).

Voelcker (1876), who gave two analyses quoted below, believed Falkland Island guano to be superior, i.e., richer in nitrogen, to that from Patagonia:

	ANDERSON	VOELCKER	
H ₂ O	8.86%	33.43%	35.86%
Organic	17.10	—	—
N	1.24	4.31	4.42
(CaMg)P ₂ O ₈	21.29	32.04	22.01
CaCO ₃	14.02	2.52	5.64
Alkaline salts	—	6.22	7.34
Insol. siliceous	—	4.37	3.08

The material imported into Great Britain in 1861–1867 realized from £4.0.0 to £5.0.0 per ton, which is in harmony with the composition indicated by these analyses.

The analyses of table 33 are curious in that a relatively high N:P ratio is maintained in spite of the excessive water content. They doubtless refer to much more recent material than that analyzed by Anderson and by Voelcker, but it is very doubtful if such a

TABLE 33

	Cochon Island			Kidney Island	
H ₂ O at 105° C.	72.93%	75.62%	74.06%	63.69%	80.07%
Ign. loss	15.69	15.24	13.71	21.73	12.13
CaO	3.74	2.92	1.26	1.52	2.46
MgO	0.72	0.17	0.10	0.33	0.41
K ₂ O	0.19	0.16	0.32	0.21	0.20
Na ₂ O	0.35	0.32	0.31	0.26	0.32
SO ₃	0.09	0.14	0.10	0.21	0.08
Cl	0.20	0.38	0.36	0.17	0.27
P ₂ O ₅ total	4.22	3.48	1.22	1.55	2.66
Water sol.	1.02	0.30	0.50	0.80	0.63
Sol. in 20% citric acid but not in H ₂ O	3.06	2.98	0.61	0.44	1.69
N total	1.71	1.23	0.96	1.23	1.02
Organic	1.17	0.78	0.61	1.00	0.70
NH ₃	0.49	0.25	0.27	0.03	0.21
NO ₃	0.05	0.20	0.08	0.20	0.11

guano could have existed in any locality warmer than those places in which it was found. The water content is actually greater than that found by Ingle (1913) in what is clearly a leached sample of sea birds' dung from the coast of Ireland, which contained 47.5% H_2O with 1.25% N and 8.5% P_2O_5 .

Although small temporary accumulations of this kind of material may form in the northern Temperate and Subarctic regions, nothing comparable to the Falkland and Patagonian guanos is recorded. A projected guano industry in the Scottish Isles (Anon., 1845c) evidently came to nothing.

GENERAL ASPECTS OF AVIAN GUANO DEPOSITION

THE DATA that have been assembled on the preceding pages permit certain general problems to be examined. The first group of these problems to be considered relates to the rather insignificant role of guano deposition in the cycle of the elements in the biosphere as a whole. A brief summary of the evidence on the effectiveness of climatic and oceano-

graphic determinants of guano deposition is then presented, after which certain biological aspects of the problem are conveniently discussed. The very important paleoclimatological conclusions of the present survey are then considered. A final section summarizes the mineralogy and local geochemistry of avian guano deposits.

GUANO DEPOSITION IN THE GENERAL PHOSPHORUS ECONOMY OF THE EARTH

It is necessary to consider only phosphorus, for the ratio of the phosphorus in guano to the phosphorus concentration per unit area or volume of the biosphere is in general much higher than is the equivalent ratio for any other element. If, as will be shown, the effect of the guano birds of the world in the geochemical cycle of phosphorus is of little importance, the same is true *a fortiori* for any other element.

THE RATE OF REMOVAL OF PHOSPHORUS FROM THE OCEAN BY SEA BIRDS

In order to examine this matter it is necessary first to gain some idea of the total quantity of guano that is annually deposited on the islands and coast lines of the entire earth. For the three regions on the arid western subtropical coasts of the continents adequate estimates can be derived from the data that have been given. The following figures represent the approximate maximum annual yields on these three coast lines, on which more or less nitrogenous guano is now being deposited.

	METRIC TONS PER ANNUM
South America	170,000
South Africa	10,000
Lower California	5,000
Total	185,000

The total maximum amount of guano deposited annually on these three coasts is, even when allowance is made for small and commercially unimportant sites, unlikely to exceed 190,000 tons. Such a mass of material, if it contained the quantity of phosphorus

that is normally found in Peruvian material, would correspond to the removal of about 8800 metric tons of phosphorus from the ocean.

It is difficult to obtain any idea of the total quantity of guano deposited by the bird colonies of tropical oceanic islands and of coastal regions other than those on the western shores of the Americas and South Africa. North states that the maximum yield of Mait Island is 600,000 pounds, or 275 metric tons, per annum, and that this is probably produced by a population of the order of magnitude of millions of birds. The only analysis of material from this locality that has been published is that of Farquharson (1928) which relates to a specimen greatly contaminated by siliceous material. It seems probable that North's estimate refers in general to better material than that analyzed by Farquharson. Assuming the P_2O_5 content to be about 30%, as is usually true of tropical phosphatic guanos, the maximum production on Mait Island would correspond to about 38 tons of phosphorus removed annually from the sea. An approximate estimate of the maximum possible number of tropical islands on which bird colonies may be producing phosphatic guano can be made from the data given throughout the text of the present contribution. It would appear that it is very unlikely that this number can exceed 250, and it is quite likely that fewer than 100 islands are involved. Assuming a mean rate of production of phosphatic guano equal to the maximum rate for Mait Island, the maximum total amount of phosphorus removed from the sea and deposited as phosphatic guano on tropical and subtropical islands cannot

exceed 10,000 metric tons per year. For both phosphatic and nitrogenous islands the corresponding estimate would be 18,800. Since the individual estimates contributing to this figure are maximum values, it is almost certainly excessive. It is, however, improbable that the total yield of the areas producing nitrogenous guano would ever fall below 5000 tons except after profound disturbance and mismanagement by man, as at the beginning of the present century, so that it is reasonable to conclude that the annual mean value lies between 5000 and 15,000 tons P.

It is probable that as much, and possibly much more, phosphorus is removed from both the Arctic and Antarctic seas by the great bird colonies in these fertile regions. Portenko (1931) concludes that the guillemots of Novaya Zemlya remove 120,000 metric tons of fish annually, a quantity that would correspond to 360 metric tons of phosphorus. Removal of 10,000 tons of phosphorus from the entire Arctic Ocean would thus imply the existence of only about 30 times the total bird population of Novaya Zemlya scattered throughout the Arctic region. The Novaya Zemlya colonies may be the largest of the Arctic, but it seems unlikely that they comprise one-thirtieth of the breeding sea birds of that region. It is, however, improbable that the whole North and South Temperate seas and Arctic and Antarctic oceans would lose 100,000 tons or about 11 times as much phosphorus as is removed annually from the oceanic areas along the western continental coasts. These very rough estimates indicate that while $n \cdot 10^4$ to $n \cdot 10^5$ tons of phosphorus may be removed by birds from the sea and be deposited on breeding sites annually, the amount that is likely to form permanent guano deposits and so be lost from the ocean, unless returned by human agency, will be about 10^4 tons.

The total drainage from land surfaces into the sea is approximately $274 \cdot 10^{18}$ grams of water per year. According to Clarke's compilation of the data available in 1924, the mean content of PO_4 of this water is 0.22 milligram per 1000 grams, or about 0.07 milligram P per liter. This figure, which is based on the mean for the general salinity of river waters, including the Amazon, may

be low. Conway prefers a value of 0.34 milligram PO_4 per liter, or 0.11 milligram P per liter. Most limnologists would probably regard the last figure as too high. In view of the restricted number of available determinations of total phosphorus in the different rivers of the world, it is hardly possible to improve on an estimate between 0.05 and 0.10 milligram P per liter. Such an estimate implies that about $137\text{--}274 \cdot 10^5$ tons of phosphorus enters the sea annually from the land surfaces. The total phosphorus removed from the sea to the land surfaces by birds is evidently but a small per cent of this quantity and the amount retained as guano deposits is a still smaller fraction, of no significance in the general geochemical cycle of the element.

THE TOTAL QUANTITY OF GUANO DEPOSITED IN POST-PLEISTOCENE TIME

Although it is apparent that guano accumulation is of little importance in the general circulation of phosphorus, and *a fortiori* of other elements, it is desirable to estimate the total mass that accumulated between the close of the Pleistocene and the beginning of nineteenth century exploitation, in order to compare the estimate with that of the older deposits believed to be of Pleistocene age.

For the nitrogenous deposits of the South American coasts, fairly good estimates are available for the principal guaneras; these have been given in the text. Where no analyses have been available, the mean from neighboring deposits has been used in further computation. The phosphorus content of Corcovado guano, namely, 6.66% P, has been employed in estimating the quantity of the element on islands from Chao southward to latitude $10^\circ 30'$ S.; that of the Chincha Islands, namely, 5.56%, for the localities south to Iquique; and a mean for the Chilean guaneras, namely, 7.22%, for all unanalyzed ancient deposits on the Chilean coast. The Mejillones deposit is best considered separately; it is probably contemporary with the other ancient Chilean guaneras as Brüggén supposes, but its peculiar situation may suggest to some a greater antiquity. Where only volumes are given, a density of 1 has been assumed. The results are as follows:

	Tons P
Old deposits of Peru and Chile, due to bird colonies existing until the nineteenth century	838,760
Ancient deposits of Chile (excluding Mejillones)	537,768
Mejillones	595,000
	1,971,528

Of this quantity 500,400, or approximately one-fourth, was present on the Chincha Islands.

The African deposits are less adequately known. On the Northern Islands at least 218,000 tons of guano were present, corresponding to 8720 tons of phosphorus. From the Colonial Islands about 75,000 tons of old guano containing about 12% P appear to have been imported; this corresponds to about 9000 tons P. The whole coast therefore probably produced a quantity of guano equivalent to about 18,000 tons of phosphorus.

The original reserves on the islands of the Pacific coast of California are unknown. Within the Gulf, Raza Island is supposed to have borne 70,000 tons of phosphatic guano apparently containing about 17.2% P, and so corresponding to 12,000 tons of phosphorus. Krull regarded this island, San Pedro Martir, and the Farallon de San Ignacio as the three most important sources of phosphatic guano within the Gulf of California. If all three islands were equally important they would together have had a reserve of 36,000 tons of phosphorus. This estimate is probably excessive; it may suggest that the whole production of both the Pacific and Gulf coasts was of the order of 50,000 tons of phosphorus, but this figure is so much greater than the African estimate that it must be accepted with great caution.

In making a rough estimate for the entire world it seems best to allow 2,100,000 tons of phosphorus for all the western continental coasts and not to attempt further refinements which the inadequate African and Californian data do not properly permit.

The total quantity of phosphorus present in the supposedly post-Pleistocene phosphatic guano of the central Pacific islands has already been estimated as 211,000 tons, while

that of the western Pacific islands has been given as 53,000 tons. Since these figures include no data from Clipperton Island, Johnston Island, the Hawaiian Leeward Islands, or Flint Island as well as from a few unimportant localities, an over-all estimate of 300,000 tons for the phosphatic guano islands of the Pacific is reasonable.

The Huon and Chesterfield Islands are supposed to have borne rather over half a million cubic meters of guano containing about 30% P_2O_5 ; this may probably be taken as equivalent to 69,000 tons of phosphorus. The original estimate is likely to be excessive but is counterbalanced by the unestimated guano from the islands of the Barrier Reef region. The southern coast of Australia appears to have produced the equivalent of 2000 tons of phosphorus, and the western coasts about 24,000 tons, though there is a two-fold uncertainty in this figure. For the whole coast of Australia and the islands of the adjacent seas, a figure of 100,000 tons P seems reasonable.

The data already given for the China Sea also indicate an original reserve of about 100,000 tons P.

The islands of the western Indian Ocean bore about 300,000 tons of P_2O_5 . Assuming that about half this is of post-Pleistocene origin, which may be an underestimate, the total phosphorus deposited since the Pleistocene would be 69,000 tons. No satisfactory estimates can be made for Latham Island or the other islands off Africa or in the Red Sea. The Kuria Muria Islands yielded 37,707 tons of guano to British vessels, and this may have contained 4000 tons of phosphorus. It is probable that all the localities in the Indian Ocean and those of the few guano islands of the middle Atlantic yielded together not more than 100,000 tons P.

For the Caribbean and Cayman seas no satisfactory estimate can be made. The most important insular phosphates of the region, on Curaçao, Sombbrero, Navassa, the Swan and Cayman Islands, Redonda, and Alta Vela seem not to be post-Pleistocene. Bird Island is the only island with a modern bird colony for which there is both an estimate of the mass and an analysis. Both the estimate of 200,000 tons and the phosphorus content of 47.5% P_2O_5 are probably

excessive. If they are acceptable the island bore about 44,000 tons of phosphorus. It is, however, very unlikely that the estimate is reliable or that the analysis refers to typical material. Orchilla seems to have borne 30,000 to 40,000 tons, containing 22% P_2O_5 , or about 3500 tons, of phosphorus, probably deposited since the Pleistocene but not by a contemporary colony. From none of the other islands are the data so good. For the purposes of the present discussion, it is assumed that the Caribbean, eastern South American, and Patagonian coasts bore about 100,000 tons of phosphorus deposited since the Pleistocene.

Since the total quantity of phosphorus in stable deposits outside the tropics is very small, the quantity of phosphorus removed as guano in post-Pleistocene time may be taken as:

	TONS
Western continental coasts	2,100,000
Pacific	300,000
Australia	100,000
China Sea	100,000
Western Indian Ocean, etc.	100,000
Eastern coasts of Americas	100,000
Total	2,800,000

Of this total, the Chinha Islands bore more than one-sixth, and the Mejillones deposits more than one-fifth. The contributions of all other individual deposits are small compared to those of these two localities. Of the South American deposits, which make up over two-thirds of the total, rather over half are ancient post-Pleistocene, and rather under half from localities with contemporary colonies. In the Pacific these relationships are probably reversed. In general it is safe to conclude that roughly half the guano deposits of the world were still growing during the early part of the nineteenth century and half were due to ancient but post-Pleistocene bird colonies.

THE TOTAL QUANTITY OF PHOSPHATIC GUANO IN SUPPOSED PLEISTOCENE DEPOSITS

Turning now to the well-elevated islands, the deposits of which appear to be Pleistocene or possibly, according to some investigators, late Tertiary, fairly good data are available for the important islands of the Pacific area

and for Christmas Island, Indian Ocean. For the western Indian Ocean, an arbitrary assignment of half the reserve to post-Pleistocene and half to Pleistocene deposits has been made. The islands of the Caribbean and Cayman seas again introduce the most significant uncertainties, as no adequate estimates are available for any of the important localities except Navassa. On this island there appear to have been between 700,000 and 850,000 tons of phosphatic rock, containing 96,000 to 117,000 tons of phosphorus. The British statistics indicate that 285,594 tons of phosphatic guano, unenumerated manures, and rock phosphate were shipped from the British West Indies, Haiti, and Santo Domingo between 1852 and 1892. Some material must have gone to continental European ports. Much phosphate, particularly from Navassa and Sombrero, was certainly brought to the United States, though no adequate statistics are available. From Curaçao it is known that 624,000 tons were exported before 1924 and that the deposit is still being worked. From Little Curaçao 100,000 tons of phosphate were removed early in the history of exploitation of the region. It is probably safe to conclude that the total quantity of phosphate removed from the islands now exhausted was of the order of 1,000,000 tons and to assume an original reserve of 2,000,000 tons for Curaçao. Assuming 15% P, corresponding to 32.7% P_2O_5 , the phosphorus in the ancient deposits of the region would be 450,000 tons. It is obvious that such a figure is little better than a guess, but it is small compared to the original phosphorus reserves of some of the better-known localities, so that it will not introduce great errors into the estimate for the world.

	TONS
Makatea	5,000,000
Ocean Island	3,800,000
Nauru	15,400,000
Kita Daito Jima	860,000
Okino Daito Jima	860,000
Angaur	405,000
Other western Pacific islands	212,000
Christmas Island	5,400,000
West Indian Ocean	69,000
Caribbean and Cayman seas	450,000
Total (to three significant figures)	32,500,000

A few localities, notably Saldanha Bay and Walpole Island, are omitted for lack of information but would certainly not change the total significantly.

The Pleistocene deposits are strikingly greater than those of post-Pleistocene time. Moreover, only two groups of the latter, namely, those of Mejillones and of the Chincha Islands, are quantitatively comparable to the more moderate of the large Pleistocene deposits such as Angaur. With these data alone before us we should be justified in concluding that the Pleistocene period was characterized by intense phosphatization, though it may not yet be possible to exclude the hypothesis that the process had already begun in the Pliocene. It is furthermore evident that the time span of the Pleistocene, though greater than that of the post-

Pleistocene, is not the only factor involved in this immense phosphatization, because the Chincha Island deposits were evidently of quite recent origin, while the Mejillones deposit had probably stopped forming at a fairly remote post-Pleistocene date. There is no suggestion that these two deposits were large because they took a long time to form; it rather appears that they were large because they formed under peculiarly favorable circumstances. It is therefore reasonable to suppose that the great Pleistocene deposits are due to the existence, at times during the Pleistocene, of circumstances far more favorable to guano deposition than are known today outside the Pacific coast of South America. This matter will be discussed in greater detail in a succeeding section.

CLIMATIC AND OCEANOGRAPHIC DETERMINANTS OF GUANO DEPOSITION

RELATION TO PRECIPITATION

While some contemporary deposition of guano is certainly occurring on bird islands that are widely distributed throughout the Pacific, the atolls that were the sites of bird colonies during the last century and from which at least 100,000 tons of phosphatic guano were removed are strictly limited to the equatorial dry belt south of the Doldrums and in the vicinity of the equatorial divergence. These islands, notably Howland, Baker, Jarvis, Malden, and Enderbury, will constitute a standard with which other localities can be compared. Apart from the islands of the western coasts of the continents, on which more or less nitrogenous guano is deposited, it is doubtful whether any other deposits actually produced by contemporary colonies equaled those of these five islands. San Juan de Nova in the Mozambique Channel may have yielded a like amount, but it is uncertain that this was produced by a modern colony. All five islands evidently have mean annual rainfalls of well under 1000 mm.

Palmyra, Washington, and Fanning Islands, with rainfall over 2000 mm. per annum, clearly have no significant deposits formed by contemporary colonies, though there is evidence of old guano on Palmyra

and Fanning and phosphatized soil and mud are clearly forming on Washington, in part owing to its very peculiar physiography. Of the guano islands in other parts of the tropical oceans the islands of the China Sea, which are evidently very humid but which are not all occupied by modern bird colonies, and Latham Island, which may have a mean annual precipitation of 1500 mm., seem to be the wettest, though some of the islands of the Subantarctic region which have produced a little guano may be still wetter. Hague (1862) long ago realized that the incidence of phosphatic guano in the Pacific was determined by precipitation. Holzschneider, who alone has considered the matter quantitatively, supposed that the isohyet of 2000 mm. set a limit to the deposition of phosphatic guano, but as he did not distinguish between modern and ancient post-Pleistocene deposits, his estimate is much too high.

In general it would seem unlikely that large deposits will form on any island receiving much more than 1000 mm. of rain per year, or any discrete deposits at all when the precipitation is over 1500 mm. per year. Where colonies of tree-breeding species of sea birds inhabit wet islands very considerable amounts of phosphate are certainly added to

the soil, but it has not been demonstrated that this process can produce a consolidated layer of phosphate in the lower soil horizons. At Rose Atoll, the only adequately studied locality, no such phosphatic layer occurs.

RELATION TO UPWELLING

The existence of the great deposits on the western continental coasts is so obviously related to the enhanced fertility of the seas, directly due to upwelling, and to the aridity of such coasts, indirectly due to the same cause, that further comment is unnecessary.

The central Pacific islands, on which deposition has occurred during the past hundred years and on which large reserves of over 100,000 tons of phosphatic guano were present, appear to be associated with the equatorial divergence in the Southern Equatorial Current. The few deposits on the eastern coasts of Africa are probably to be associated with upwelling on the coastal margin of the Somali Current during the season when that current is flowing. There is also evidence of enhanced productivity, due to vertical mixing, at the southern end of the Red Sea, and off the Kuria Muria Islands. The southern part of the Caribbean, off the coast of Venezuela, is the most productive region of that sea and probably owes a part of the fertility to vertical mixing. The immense bird colonies of the Subantarctic Islands are obviously related to the great fertility of the Subantarctic seas.

No really adequate information exists about the other important regions producing guano, namely, the Hawaiian Leeward Islands, the seas around Australia, the China Sea, and the western part of the Indian Ocean. It is probable that there is some upwelling along the Great Barrier Reef and also along part of the coast of Western Australia; there is, however, no evidence that the guano islands are associated with the upwelling zones. The hydrography of the China Sea,

with its elaborate system of reefs and sharp seasonal reversals in current, is certainly complicated in its local detail; it is not unlikely that at some seasons marked vertical mixing occurs off the Dangerous Ground (Herbert Warfel, verbal communication). In all cases where a small island surrounded by deep water is set in the course of a current some local vertical mixing may be expected, as Orr (1933) has pointed out. Thomas S. Austin indicates (verbal communication) that evidence of such mixing was found in the vicinity of Bikini Atoll. It is therefore quite likely that all the phosphatized oceanic islands are surrounded by areas of water that are somewhat more productive than is the adjacent ocean. If this be so it is obvious that slightly enhanced productivity would also be expected around many unphosphatized islands. The relationship of upwelling to guano thus becomes somewhat indefinite if we consider the whole series of phosphatized islands without taking into account the quantities of guano and phosphate originally found on them. The significant relationship is presumably that the really massive deposits on the western continental coasts, culminating in the guaneras of the Chincha Islands and of Mejillones, were formed by birds fishing in water of notorious fertility, characterized by intense upwelling. In the central Pacific the largest phosphatic deposits of recent origin are again in a zone of enhanced fertility. All the recent deposits outside the western continental coasts and the dry equatorial Pacific region are small compared to the deposits within these areas. It is not yet possible to indicate to what extent these small deposits owe their existence to local upwelling, though in some cases, particularly in the southern Caribbean, off the eastern coast of Africa, and in the Red Sea, it is very probable that a relation between phosphatization and the enhancement of productivity by special hydrographic patterns does exist.

BIOLOGICAL ASPECTS OF GUANO PRODUCTION

TAXONOMIC STATUS OF THE GUANO BIRDS

The properties that will make any species of bird an ideal producer of guano are that it should be highly social, breeding in large colonies, that it should use a minimum of

material other than guano in constructing its nest, that it should not burrow excessively into the soil or old deposits on the nesting site, and that it should deposit an appreciable fraction of its excreta at the nest. A number

of individuals of a large species occupying a given area will obviously be more effective than an equal number of a small species, though they may, owing to surface-volume relationships in metabolism, be less effective than in equal mass per unit area. Fish-eating species will probably be more effective than invertebrate-feeding forms, at least where phosphatic guano is being deposited.

Taxonomically the guano birds belong to four orders, the Sphenisciformes, the Procellariiformes, the Pelecaniformes, and the Charadriiformes. The distribution of the guano birds is not in proportion to the total number of species in these four orders, even when the bulk of the Charadriiformes are excluded and only the preëminently marine families are considered.

	TOTAL NUMBER OF SPECIES ^a	NUMBER OF GUANO BIRDS ^b
Sphenisciformes	17	5 (6)
Procellariiformes	93	1 (6)
Pelecaniformes	54	11 (15)
Charadriiformes (Lari- dae and Alcidae)	104	2 (5)

^a Mayr, 1946.

^b Figures in parentheses include species recorded as producing guano but of negligible quantitative importance.

It would thus appear that while roughly one-quarter of the species of the Sphenisciformes and Pelecaniformes may produce guano deposits under some conditions, very few of the numerous species of the other two orders are involved. The penguins satisfy the various requirements of an ideal guano bird very closely. They are, however, almost entirely restricted to the Southern Hemisphere, reaching even subtropical latitudes only on the South American and South African coasts. Though almost all of the Falkland Island and Patagonian guano, much of the southwest African and some of the Peruvian deposits, and whatever guano was produced in the Subantarctic Islands of New Zealand were derived from penguin droppings, the limited distribution of the group prevents these birds from having had a part in producing the main deposits of phosphatic guano.

The only member of the Procellariiformes

of any importance is *Diomedea immutabilis*, which was doubtless a guano bird of significance on Laysan and other islands of the Hawaiian Leeward chain and on Marcus Island. *D. nigripes* may have contributed a little guano to the deposits on these islands and on Johnston Island, and *D. cauta* is known to produce quantitatively insignificant deposits in the Bass Strait region. *D. albatrus*, or a precursor, may have been responsible for the large ancient deposits on the Daito and Riu Kiu Islands. The most difficult problem presented by the Procellariiformes is that of *Pelecanoides garnotii*, regarded by Raimondi as the most important guano bird of Peru. The reasons for regarding this judgment as erroneous have already been given. Though a number of the Procellariiformes are social, the habit of nesting in burrows exhibited by many species militates against their being important guano birds.

The Pelecaniformes include all the most important guano birds. Four of the six living families of the group are involved. Of these the Pelecanidae and Phalacrocoracidae have remained littoral birds of continents or continental islands, while some of the Sulidae and Fregatidae have put out to sea and breed on oceanic islands. The immense sizes of cormorant populations which can develop in favorable circumstances have made the social species of the western continental coasts the most productive of all guano birds. Within the genus *Phalacrocorax*, however, great differences in behavior exist, and these differences are reflected in guano production. On the Peruvian coast *Phalacrocorax bougainvillei* is not merely the most abundant, but is also the most social, species. Apart from the size and sociability of a species the most important additional requirement is that the nest be composed almost entirely of guano. In abundance, tendency to form aggregates, and in its capacity to produce a nest composed almost exclusively of guano, *P. bougainvillei* is vastly superior to the other cormorants of Peru, while *P. gaimardi* is certainly the least satisfactory in these respects. The great interest shown even by *P. bougainvillei* in extraneous nesting materials indicates that the construction of a pure guano nest is tolerated rather than preferred. The development of such a tolerance is

shown by other birds on the western coast of America, notably by *Sula variegata*, and apparently by *S. nebouxi*, when compared with *S. leucogaster*. On the California coast *P. penicillatus* is conspicuously superior to *P. auritus albociliatus* in this respect. The proportion of the excreta deposited at the nesting site may also be a specific psychophysiological character of importance. It has already been pointed out that in the case of *P. bougainvillei* the available estimates of food intake and guano production allow no significant margin for loss of guano to the sea. The birds would therefore seem to retain their excreta until they are on land.¹ If this conclusion is correct it is legitimate to inquire whether such a habit is not widespread, though by no means universal, in the *Pelecaniformes* and may explain in part the significance of birds of that order as guano producers. There can be little doubt that there are characteristic modes of excretory behavior in the genus *Sula*, as is apparent when the guano nest of *S. variegata* is compared with the guano ring often noted around the almost non-existent nest of *Sula dactylatra* and shown in the photograph here reproduced from Murphy (pl. 16, fig. 1; cf. pl. 16, figs. 2, 3).

The guano of tropical oceanic islands must be produced largely by species of *Sula* and *Fregata* and by the few species of *Charadriiformes* which contribute to persistent deposits. It is difficult to assess the importance of *Fregata*. Where this genus inhabits an island also occupied by boobies it appears to live largely or even exclusively by cleptobiosis, forcing the *Sulidae* to disgorge their prey in the air. It is reasonable to suppose that if *Fregata* were absent more boobies would be present, so that there would be no increase in production due to the presence of the frigate birds.

Of the various species of *Sula*, *S. variegata* is endemic to the region inhabited also by the guanay and, in all its relevant characters, is obviously almost as good a guano bird. *S. nebouxi*, though not regarded as a truly

social species by Murphy and by Vogt, clearly can form dense colonies and is certainly responsible for part of the deposits on the Lobos Islands and on San Pedro Martir in the Gulf of California.

The significance of the two tropicopolitan species of ground-nesting boobies, *Sula dactylatra* and *S. leucogaster*, is harder to assess. On the Pedro Cays, C. Bernard Lewis was told that *S. d. dactylatra* was the best producer of guano. *S. d. melanops* is presumably the chief guano bird on Latham Island. It seems probable from the observations made at these two localities and also in the Revillagigedo Islands (Anthony, 1898b) that *S. dactylatra* in general remains at its breeding station for a greater proportion of the year than does *S. leucogaster*. For this reason it is likely to deposit more guano per bird than does the latter species. *S. l. leucogaster* and *S. d. dactylatra* are evidently the main contributors to the deposit on Boatswain Bird Island, Ascension, but it is not possible to ascertain which species was the more important. *S. leucogaster nesiotus* appears to have been responsible for the deposit on White Rock in Las Tres Marias Islands. *S. l. brewsteri* may have been of some significance on San Pedro Martir in the Gulf of California, though Goss indicates that it used more extraneous nesting material than *S. nebouxi* which species nested on flatter areas and in greater number than did Brewster's booby. *S. l. leucogaster* seems definitely to have been the chief guano bird on Ave de Barlovento in the Venezuelan Leeward Islands and on Alcatraz Island, the only guano island off the northwest coast of Africa. Vogt regards neither *S. leucogaster* nor *S. nebouxi* as sufficiently social to produce important annual increments in guano on the islands of the Gulf of California, though he admits that the slow accretion of the droppings of these birds could have produced the old deposits.

It is difficult to evaluate the role of the very few members of the *Charadriiformes* that may produce guano. The only certain records relate to terns, principally *Sterna fuscata*, which evidently is the main contributor to the guano deposits of the sand cays of the western Indian Ocean. The present yield of Mait Island is presumably chiefly due to *S. fuscata*, though *Anous stolidus plumbei-*

¹ Since the above was written, Mr. W. B. Alexander has made, in conversation, the very interesting suggestion that the retention of feces by species fishing by sight in great flocks would be advantageous, because random defecation would soon render the water, in the neighborhood of the flock, distinctly opaque.

gularis may be of some significance. Outside this area there is presumptive evidence that these species shared with *Diomedea immutabilis* in the production of the Laysan deposit. There is also strong probability that the guano of Houtman's Abrolhos was mainly produced by *S. fuscata serrata* with some contribution from *Anous stolidus gilberti*. It is curious that the only definite record of the species of bird producing a deposit on the west coast of Australia refers to *S. bengalensis torresii*, a species not otherwise known to be of any importance. In spite of these records there are two rather definite indications of the ineffectiveness of terns in the production of guano. The first relates to Wideawake Fair, Ascension, which does not develop a guano covering in spite of the immense tern population; the second is the indication given by C. Bernard Lewis that sooty terns are of little or no importance as sources of guano on the cays off Jamaica. These observations, which cover all the cases in which specific identification of guano birds on tropical islands yielding phosphatic guano have been made, are obviously most inadequate. No clear indication of what species really formed the deposits on the dry Line and Phoenix Islands has been given. Terns are now the commonest birds on these islands, so that it has therefore probably been tacitly assumed that the guano deposits were formed by *Sterna fuscata* and *S. lunata*. Admittedly the slope of the main tern colonies on these islands would be towards the lagoons, while Wideawake Fair slopes seaward. It is evident that on an island such as Malden the guano deposits were not concentrated in the lagoon but remained more or less *in situ*. In view of the observations made on Ascension and on the Jamaican cays, it may be reasonable to suggest that perhaps boobies were once the chief guano birds of the Line and Phoenix Islands. If the document put together by Mr. Llewellyn Howland can be trusted on this point, it not unlikely that *S. leucogaster* was indeed the commonest bird on Howland Island before the guano diggers came to the island.

The observations available at present chiefly indicate that even if a series of bird colonies of a given area each consist of a certain mass of birds, there is no certainty

that the same amount of guano will be deposited by each colony. Not only physiography and climate but the kind of bird appears to be of importance. There is moreover a distinct possibility that different colonies of the same species may behave somewhat differently, for it is by no means certain that merely because two populations receive the same specific name their innate behavior and reaction to environmental variables will be identical. At present it is almost impossible to gain any knowledge of the part played by subspecific differences in behavior or physiology in determining guano production. That physiological differences between morphologically identical populations do occur is indicated by the fact that on Latham Island about one-third of the breeding specimens of *Sula dactylatra melanops* are, according to Moreau, in immature plumage, while on the Amirante Islands and islets of the Farquhar and Cosmoledo Atolls, only birds in mature plumage are found incubating. The Latham Island colony in this respect exhibits a tendency apparently found among other birds in colonies on islands uninhabited by related species, and presumably due to the degenerative loss of patterns that act as specific sign stimuli, under conditions where the possibility of interspecific mating is reduced to a minimum.

One case is known which perhaps suggests that innate differences of behavior between subspecies play a part in determining guano production. Vogt writes of *Sula leucogaster brewsteri* as a territorial rather than a gregarious species and attributes the relatively small and scattered deposit produced by this bird on the islands of the Gulf of California to this. North (1912) quotes observations of Macleay that *S. l. plotus*, on Bramble Cay in the northern part of the Great Barrier Reef, placed its nests so close together that it was difficult to avoid walking on them. It is possible that environmental factors prevent crowding on the islands of the Gulf of California, but the account of the birds at Bramble Cay is hardly consistent with Vogt's idea of the species as territorial rather than social, and it is conceivable that the different subspecies of *S. leucogaster* differ in sociality.

SIGNIFICANCE OF THE SIZE OF BREEDING COLONIES

A matter of very considerable importance is raised by Darling's (1938) observations that a minimum number, greatly in excess of a single pair, is needed to initiate a colony of certain species of sea birds. Different aspects of the biology of the various social species underlie need for a colony of minimum size, and Darling's ideas on social courtship are clearly not the only concepts that can be used to explain the phenomena (Bullough, 1942).

Vogt found that in the guanay the colony grows peripherally and does not show synchronization in the reproductive activities or the socio-sexual phenomena which Darling considers to underlie synchronization. Yet Vogt regards the existence of large colonies as conferring advantages on the individuals in ways that have already been discussed. He indicates (*in litt.*) that the minimum size of the colony in *Phalacrocorax bougainvillei* is probably about 10,000 birds. Vesey-Fitzgerald likewise found no evidence of social courtship in *Sterna fuscata* but noted that single pairs were far less disposed to defend their nest than were aggregated pairs.

In the guanay, a species in which a breeding group draws other individuals into the colony, and in which there is no evidence that the birds habitually return to specific islands to breed, the failure of a small colony on any one of the numerous Peruvian islands would not affect the population of that island in a subsequent season. In the case of a species such as the sooty tern, breeding on an isolated oceanic island, any catastrophe leading to a decline in the population to below the critical minimum might lead to irreversible depopulation. This phenomenon may prove to be of importance in regions which are only just dry enough to permit the destruction of herbaceous vegetation by ground-breeding species such as *Sterna fuscata*.

CHANGES IN TERRESTRIAL BIOTA CAUSED BY BIRD COLONIES

Wherever a large bird colony exists, the birds may be regarded as dominants in the sense that Clements and Shelford use the term, since they determine the nature of the

community of the area occupied by the colony. Three aspects of this process must be considered, namely, the positive effect of the bird colonies in promoting certain elements of the biota, the negative effect of the colonies, suppressing certain elements, and the competition between the birds and other organisms. In general the flora alone need be considered. Bird colonies are naturally the habitats of some predators and of numerous parasitic and scavenging animals, and of predators upon these, but in general the quantitative importance of such species is not great. The interesting case of the endemic pipit *Anthus steindachneri* on Antipodes Island, which feeds on flies breeding in penguin droppings and so is dependent on the sea bird colony, may, however, be recalled; other similar cases doubtless exist. On wet islands birds may have a positive effect on the vegetation. In many cases it is quite likely that species encouraged by the presence of birds are actually merely tolerant and exist solely because the deposition of bird droppings and mechanical disturbance prevents the colonization of the site by other species that are otherwise widespread but less tolerant of the peculiar conditions set up by the birds.

The large subarctic and arctic bird colonies, though they do not produce stable guano deposits, nevertheless have a profound effect on the vegetation in the neighborhood. This has been emphasized by Lynge (1934) who regards the presence of large bird colonies as of primary importance in promoting rich vegetation in the Arctic. He believes that the restricted nature of the flora of the northeast coast of Greenland is largely due to the absence of large bird colonies on a coast washed by seas which can remain covered with pack ice during the breeding season. In Arkhangel Bay, Novaya Zemlya, the immense bird colonies are largely responsible for an extraordinary development of the lichen and moss flora. Lynge found that the phanerogamic flora of a particularly favorable hill, set in a position to catch the sun, did not differ greatly from that of the bird cliff, but that the mosses and lichens were qualitatively and quantitatively very much better developed in the region fertilized by the birds than on the Flower Hill, where the

favorable circumstances were primarily due to sun and good drainage. No fewer than 208 species of lichen were found by Lynge during eight days' work on the bird cliffs of Arkhangel Bay. Among flowering plants, *Saxifraga cernua*, *Cochlearia*, and *Alopecurus alpinus* are particularly mentioned as of great luxuriance on the bird cliff.

The association of nitrophilous lichens with bird colonies is not confined to high altitudes, as has already been indicated in the account of Necker and Nihoa Islands in the Hawaiian Leeward chain.

It is probable that a comparable situation exists on the Subantarctic Islands of New Zealand. The very remarkable occurrence of the endemic *Senecio antipodus* on Antipodes Island, a plant that is apparently determined in its distribution by the fertilizing effects of nesting giant petrels, has already been mentioned.

The factors regulating the competition between *Pisonia* and other trees on the wetter, slightly elevated atolls of the tropical Pacific may in some cases involve the action of bird colonies. On Palmyra, *Pisonia* occurs on wetter acid soil on phosphatic hard pan, *Pandanus* and *Cocos* on drier, more alkaline soil on unphosphatized coral debris. What part the phosphate may play in this is uncertain, but at least *Pisonia* can grow luxuriantly in the phosphatic soil of Rose Atoll.

Considering now the destructive effects of guano birds on vegetation, both the mechanical disturbance and the chemical action of guano may be expected, but, as indicated below, the outcome of the processes destructive to plants certainly vary with the rainfall and are most severe where there is least opportunity for the guano to be washed away.

On Antipodes Island, which with the other Subantarctic Islands of New Zealand has been well studied by Cockayne, the negative effects of bird colonies appear to be little marked.

On the wet meadows of The Snares, however, penguins apparently produce a successional cycle. The trampling of the birds and their fouling of the colony site with guano produce a bare expanse of mud which is finally abandoned. The over-fertilized ground is occupied by *Tillaea moschata*, normally a halophyte, with scattered *Colobanthus*

muscoides, normally a coastal rock plant. These are gradually replaced by the tussock grass, *Poa foliosa*, and the site is restored to its original state.

The Bounty Islands lack vascular plants altogether, which may in part be due to the immense bird colonies of the group.

On tropical islands it seems usual for the adverse effect of bird colonies on vegetation to be expressed most markedly on the drier islands. Where the rainfall is 2000 mm. or more a rich arboreal vegetation develops, as on Palmyra, Washington, and Fanning Islands. Even when arboreal vegetation is fully established some birds apparently may destroy the trees in which they breed. *S. sula* does this in the Cayman Islands, where the inhabitants apparently found that the bird, when abundant, cleared patches of forest and fertilized the cleared areas at the same time. Vesey-Fitzgerald noted the burnt appearance of trees inhabited by this species in the islands of the western Indian Ocean. In temperate latitudes, where the climate is too humid for guano accumulation, the same phenomenon occurs in cormorant colonies; where the supply of suitable vegetation is limited the growth of a large population may tend to destroy its own breeding habitat. Kortland (1942) found this to be true of *Phalacrocorax carbo sinensis* in Holland. On the eastern North American coast *P. a. auritus* (Lesson) is known to injure such trees as it may occupy, though most colonies are found on rock ledges (Lewis, 1929).

On the wetter Pacific islands the main effect of the interaction between birds and vegetation is on the birds. *Sula sula* replaces *S. leucogaster* and *S. dactylatra*, which breed on the ground, and *Sterna fuscata* is replaced by arboreal terns such as *Gygis alba* and *Procelsterna cerulea*, both species that can also breed on rock ledges. The noddy, *Anous stolidus*, can occupy either habitat.

On the driest islands little or no vegetation exists, even in the absence of a bird colony. On four of the major guano islands of the Line and Phoenix Islands, and on the less significant members of the latter group also, there is no evidence that the presence of bird colonies was of any importance in reducing the density of the scanty vegetation cover.

Howland Island provides what is probably

the limiting case, at the arid end of the scale of the interaction of birds and vegetation. *Cordia* trees can evidently just survive on the island but do not reproduce. They provide nesting sites for a tree-nesting booby, presumably *S. sula*, but when this bird is present, an undergrowth of *Boerhaavia* cannot develop. The presence of the *Cordia* trees is certainly due to Polynesian visitors, probably in the eighteenth century, and the failure of the trees to reproduce is doubtless due to the aridity of the island, so that here the effect of the birds is mainly on the undergrowth and not on the tiny stand of arboreal vegetation.

On the Hawaiian Leeward Islands, which are evidently somewhat wetter than the Line Islands, a very rich though mainly herbaceous vegetation existed on Laysan prior to the introduction of rabbits, in spite of its enormous bird colony. As far as can be ascertained the reconstitution of this vegetation, after the death of the rabbits, has not been unfavorably influenced by the birds. In certain other cases there is, however, evidence that competition between birds and plant cover can occur and that its outcome is regulated by climatic factors.

In general, it would appear from the foregoing discussion that the driest islands would be without a vegetation cover even in the absence of a bird colony, while the wettest islands always would have a rich arboreal vegetation, often used as a breeding site by tree-nesting species, but only locally modified or inhibited by the presence of such birds. There are, however, a number of groups of islands which are too dry, at least at certain seasons, to support tropical forest, but which, at least when undisturbed, have well-marked associations of herbaceous plants. On some of such islands it is probable that relatively intense competition between birds and plant cover takes place, though if the vegetation wins, the effect on the bird fauna is to replace species breeding on the ground by species breeding in bushes and not to abolish the bird colony entirely. The evidence already given, notably from Rose Atoll, suggests that such a replacement would prevent the deposition of a stable discrete layer of guano.

The competitive process is best illustrated by Vesey-Fitzgerald's observations on *Sterna*

fuscata in the western Indian Ocean. Although the story that birds sprinkle vegetation with sea water could not be confirmed, their breeding activities have a deleterious mechanical and chemical effect which kills all the plants in those areas occupied by the large colonies. C. Bernard Lewis, however, informs me that his unpublished observations indicate that in the Caribbean region complete artificial destruction of the scanty vegetation of the cays is prejudicial to *S. f. fuscata*. It is greatly to be hoped that a full report of these interesting observations will shortly be available. It is probable from Vesey-Fitzgerald's account that the need for cover in certain parts of the tropics is dependent on the relation of the normal breeding season to the season of maximum temperature. Chicks hatched late in August on the cays of the western Indian Ocean frequently die of sunstroke, as the monsoon has ceased to blow. Single birds, however, may actually be strangled in considerable numbers by *Cassytha* vines, so providing a most striking case of reciprocal competitive relations between two very diverse species. Small colonies seem to have a lower effective reproductive rate than do large, in part because they are less effective in defense of the nests, so that the invasion of any vegetated area is likely to be easy only when it is taking place at the margin of a large growing colony. The initiation of new colonies and the reestablishment of old colonies of any obligate social species, which have been disturbed, are likely to be difficult in any circumstances, and wherever the vegetation is of a kind inimical to the terns, such difficulties will be increased. It is very likely that in groups of islands of moderate rainfall the destruction of a colony is irreversible even when other islands exist in the same group from which a new population could be recruited. This may explain the fact that in some island groups the different members of the group differ greatly in their ecology. This would seem to be true not only of the region where Vesey-Fitzgerald worked, and where Bird Island and Dennis Island provide a striking if somewhat artificial case, but also of the islands of the China Sea, Houtman's Abrolhos, and possibly some of the islets of the Caribbean region.

It is reasonably certain that rainfall must

be the primary factor in setting the limits to the ecotone or zone of tension within which the kind of competition just discussed may be supposed to operate. Many other factors may also be involved, and it is therefore difficult to set any limits of precipitation that would define the tension zone. If the phenomena have been correctly interpreted above, they may be looked for on island groups having rainfalls from rather under 1000 mm. up to 1500 mm. per year. A fascinating field for further research on the interaction of precipitation, bird colonies, and vegetation on tropical islands is evidently open to anyone in a position to take advantage of it. In any such work it is very desirable to bear in mind certain of the theoretical aspects of competition between species.

As Volterra (1926), Gause (1934, 1935), and many others have pointed out, the competition between two species forming populations N_1 and N_2 , in an area that can support maximum populations of either species, K_1 or K_2 , may be expressed

$$\begin{aligned} 1. \quad \frac{dN_1}{dt} &= b_1 N_1 \left(\frac{K_1 - N_1 - \alpha N_2}{K_1} \right) \\ 2. \quad \frac{dN_2}{dt} &= b_2 N_2 \left(\frac{K_2 - N_2 - \beta N_1}{K_2} \right) \end{aligned}$$

Equilibrium with survival of both species is possible only when

$$\begin{aligned} K_1 &> \alpha K_2 \\ K_2 &> \beta K_1 \end{aligned}$$

which implies, as can be seen by substituting K_2 for N_2 in equation 1 and K_1 for N_1 in equation 2, that there is always space available for one species that the other cannot use, in other words, that the two species do not have identical niches. Whenever the inequalities are of the form

$$\begin{aligned} K_1 &< \alpha K_2 & K_1 &> \alpha K_2 \\ \text{or} & & & \\ K_2 &> \beta K_1 & K_2 &< \beta K_1 \end{aligned}$$

or, if $K_1 = K_2$,

$$\alpha > 1 > \beta \quad \text{or} \quad \alpha < 1 < \beta$$

competition ends in the complete displacement of the species characterized by the lower coefficient of competition.

These relationships are observed only

when the coefficients remain constant. It is known that the values may be determined by environmental factors. Since the environment of any individual of a social species is largely determined by the size of its own population, the case in which the coefficients are not constant but are proportional to the number of individuals present is particularly important. It has been pointed out (Hutchinson, 1947) that where the coefficients increase with increasing population size, the result in nearly all natural cases will depend on the initial numbers of the two species. Though in many cases it is probable that the effect of competition between sea birds will depend on environmental factors, it is also very likely that in many other cases the direction in which competition proceeds will depend on the absolute or relative numerical strength of species present when a new complex colony is founded. This is implied in Vesey-Fitzgerald's remarks about *Sterna fuscata* and *Anous stolidus pileatus* and is also likely to be true in the competitive relationships observed between the former species and the plant cover. It is not impossible that some of the changes in the population of the Peruvian islands may involve the same principle.

Whenever a gradient in environmental factors capable of influencing the direction of competition exists we may expect the development of zonation (Gause and Witt, 1935). This term is here used to imply the development of two or more areas of colonization of different species which have sharper contiguous boundaries than the gradient in the environmental variables would lead one initially to suspect. The environment will vary continuously, the specific composition of its biota will vary discontinuously. This results from the fact that, though the values of the coefficients change continuously, there is a definite point in this continuous process at which the relationship of the coefficients determining the direction of competition changes abruptly. In the case in which $K_1 = K_2$ the change from $\alpha > 1 > \beta$ to $\alpha < 1 < \beta$ will determine such a point. Since it is probable that in the Indian Ocean and also on such Pacific islands as Laysan the zonal arrangement of birds is of importance in guano production, any factors leading to

the establishment of zonation are likely to be of significance.

CHANGES IN LITTORAL PRODUCTIVITY DUE TO BIRD COLONIES

If we consider a coast line along which some upwelling occurs, a gradient in nutrient concentration from the shore seaward is to be expected. In the upwelling zone a high concentration of nutrients or phytoplankton or both, and far out to sea low concentrations of both, will be observable. Since upwelling necessarily implies divergence of water from the coast, even where the cold coastal and warm oceanic waters are sharply distinguishable, some horizontal mixing, lessening the slope of the gradient, must occur. In the case of oceanic islands in extended upwelling zones, the gradient will certainly be very gentle, and where little upwelling occurs there will be little gradient.

If a bird colony is situated on such a coast or island, part of the upwelling nutrients will finally be deposited on the island. Wherever any of this material is washed back by rain or wave action into the sea, there will be locally and momentarily a much greater concentration of nutrients where the guano solution returns to the ocean than at any other place. The result of a very large bird colony on a section of coast line or on an island, whenever climatic conditions and the form of the substrate of the colony permit guano to be returned to the ocean, will be to steepen the nutrient gradient. Nutrient elements that without the birds would tend to remain in the bodies of fish in the peripheral part of the trophophoric field of the colony, and on

the death of the fish would presumably be distributed widely through the general circulation of the ocean are concentrated by the birds on and around the island. The result will be increased littoral productivity and probably increased littoral fish production. If the latter occurs the birds will not have to move so far out to sea for their food, and a steady state condition will be set up.

It is improbable that the process just described would be of any great significance off the Peruvian, Californian, or South African coasts, where it would be poorly marked owing to the low rainfall and obscured by intense upwelling. It is quite likely to be recognizable around small oceanic islands with bird colonies, and has been invoked by Wheeler to explain the greater fertility of the ocean around Cargados Carajos, or St. Brandan's Islands, than around other islands in the western Indian Ocean. Wheeler does not consider the cyclical aspect of the guano fertilization that he believes to occur around St. Brandan's, but it is evident that a mechanism of the kind just described is the only one that could be implied by his suggestion. Although at first sight such a mechanism would hardly seem likely to be of any importance, Wheeler's account suggests that in some cases the possibility of its occurrence must be considered very seriously, not merely from a purely scientific but also from an economic point of view. It is, in fact, conceivable that large bird colonies, far from reducing the commercial catch of fish by competition, may actually increase the catch by a process of biogeochemical concentration.

PALEOCLIMATIC CONCLUSIONS

SIGNIFICANCE OF PHOSPHATIC DEPOSITS ON WELL-VEGETATED, SLIGHTLY ELEVATED ATOLLS; POSSIBLE CORRELATION WITH CHANGES ON WEST COAST OF SOUTH AMERICA

Throughout the Pacific, and apparently also in the China Sea, the western Indian Ocean, and the Caribbean, many low islands bearing phosphate are now found covered with vegetation and with no signs of ground-breeding bird colonies.

In the Pacific the following islands, which are no more elevated than the dry Line and Phoenix Islands, belong in this category:

Palmyra
Fanning
Flint
Caroline
Bikar
Ebon
Ngatik
Greenwich

Gaferut
Togobei
Sonsorol, Panna, and Puru
Purdy Islands
Manu, Ava, and Wirwutu in the Ninigo Islands

Six of these islands, Palmyra, Caroline, Bikar, Ebon, Ngatik, and Greenwich, must be regarded as unelevated atolls. Palmyra certainly has no raised reef rock, and the fragmented nature of the land surfaces of the other members of this group suggests that they are formed solely of debris that has accumulated on the atoll rim.

The change in sea level that has produced the slightly raised atolls of the Pacific is in general regarded as post-Pleistocene. It has been discussed by Wentworth and Palmer (1925) who recognize a very widespread and supposed eustatic fall in sea level, of the order of 1 to 3 meters, throughout the central Pacific, and by Tayama (1939) who terms the raised beach in the western Pacific, formed prior to the fall in sea level, the post-Peleliu strand line. Daly (1934) suggests that the fall is not eustatic but is due to plastic readjustment of the Pacific floor to its additional post-glacial load of water.

The emergence of Togobei in its modern form is definitely ascribed by Tayama to the retreat of the sea from the post-Peleliu strand line, and there can be little doubt that the present condition of the Purdy Islands and the phosphatized Ninigo Islands is due to the same event.

The phosphatization of Togobei and the Purdy Islands must have taken place subsequent to their emergence. The unelevated atolls that bear phosphate were formed by the accumulation of reef debris on preëxisting platforms at about the time that the modern sea level was established. It appears therefore that at this time, or shortly after it, conditions for extensive phosphatization were very much more widespread in the equatorial Pacific than they are today. Three hypotheses may be entertained as to the cause of this extension of phosphatization. First, it may be supposed that the extension of man throughout the Pacific disturbed the bird colonies. Against this view may be set the fact that the first four islands in the list were uninhabited when discovered by occidental

navigators, though Fanning and Washington had been visited by Polynesians, and Bikar seems to have had no permanent settlement. Second, it may be supposed that the productivity of the ocean has changed in post-Pleistocene times. It is, however, evident that a number of the islands in question lie close to the Equator and so within a zone as likely to be as productive as the waters around the drier Line and Phoenix Islands. Third, it may be supposed that the rainfall was formerly much less throughout the region. It is difficult to avoid adopting this conclusion, at least as a tentative working hypothesis. The comparison of the Purdy Islands with the Line and Phoenix Islands has already emphasized how closely the former resemble the condition that would be established if a dense tropical rain forest were to spring up on the phosphatized Phoenix Islands or on Howland or Baker Island.

Considering only the Line Islands, the observed distribution of phosphatization could be explained by the hypothesis that the equatorial rain belt formerly lay south of its present position, with its center over Christmas Island rather than over Washington Island. The latter might have had some water in its lagoon, but this could have been brackish and without a marginal zone of peat. Fanning and Palmyra, being somewhat drier than they are today, would more easily acquire phosphatic guano; Christmas Island, being wetter, would acquire none. The three dry islands on the Equator might have been wetter, but if the postulated shift of the rain belt to its present position occurred only a few thousand years ago there would still have been ample time for the accumulation of the deposits exploited in the nineteenth century. This hypothesis is in accord with that developed to explain the distribution of fossil and recent guano on the Peruvian coast, namely, that a slight shift of the thermal Equator northward occurred in the western Pacific, probably at some period in the first or second millennium B.C. There is, however, no independent evidence that the event postulated to explain the chronology of the nitrogenous guano deposits on the west coast of South America was identical with that evoked to explain the distribution of phosphatization in the Line Islands.

It is less easy to interpret the distribution of phosphate on wet post-Pleistocene atoll surfaces in the western Pacific solely on the basis of shifting rainfall zones, without a decrease in the rainfall of each zone. The whole western part of the Pacific is so much more rainy than are the central parts of the trade wind belts, that a mere change in position of the latter might not be sufficient to produce the required effect. Nevertheless some diminution in precipitation would take place on all but the most western of the islands under consideration if the equatorial rain belt shifted sufficiently far to the south.

The alternative to such a hypothesis of shifting rainfall zones is obviously a very considerable decrease in rainfall throughout the tropical Pacific; this hypothesis fits the western islands better than does the hypothesis of shifting zones. It does not explain the details of the distribution on the Line Islands, it cannot be correlated with Peruvian events, and it demands a greater change in the water economy of the earth as a whole than does the hypothesis of zonal shifting, though in other ways it may be found to do less violence to general meteorological theory. Until other aspects of the question have been considered by field workers in the Pacific, it is clearly not possible to decide between the two hypotheses. The facts seem clearly to imply climatic change, but its exact nature evidently cannot be ascertained from the evidence available at present.

Biogeographical and archaeological information may ultimately permit approximate dating of the postulated climatic change. It certainly occurred after the last emergence in the Pacific, as both atolls with and without elevated reef rock bear witness to its occurrence, and the phosphatization in the Purdy Islands and probably on Togobei implies that the lagoons of these islands were closed when the process took place. Washington and Fanning Islands have evidently been wet enough to support a population of *Conopodas a. pistos* at least long enough for some subspecific differentiation to have taken place. If Palmyra lacks this bird because it is too young, its phosphatization may have to be referred to a later time than that on Fanning. The closure of the lagoon on Washington seems to have taken place at a sufficiently

remote time for the rather distinct subspecies, *Anas streperus couesi*, to have evolved, but the peat bog cannot have started to develop until shortly before the advent of the maker of the ancient canoe discovered at the bottom of the bog. Nothing definite can be learned from any of these pieces of information, but they do suggest that if enough data on the biogeography and archaeology of all the phosphatized islands were brought together, it might be possible to develop a reasonable chronology. The archaeology of the western islands should in particular repay careful attention. At present, following the discussion given in the descriptive sections and in the preceding few paragraphs, we can only state conclusions for the whole Pacific basin in the following rather vague and general way:

1. Conditions were favorable for the deposition of guano on the Chilean coast, but not on the Peruvian coast, prior to an emergence of about 10 meters. This emergence began shortly before the oldest human inhabitants, the makers of the lower shell fish-hook culture, entered northern Chile. Guano production declined in Chile as the islands became connected to the mainland. The Peruvian deposits began to accumulate comparatively recently, probably since the first or second millennium B.C. It is suggested that prior to this time the meteorological Equator lay slightly south of its present normal mean position, and that the prevalent climatic and oceanographic regime off Peru approximated that of modern abnormal years.

2. Conditions for deposition of guano were more favorable throughout the equatorial Pacific at some period after the most recent (post-Peleliu) emergence than they are today. The distribution of phosphatic deposits on the Line Islands could be explained by a change in the position of the mean meteorological Equator of the same kind as evoked to explain the conditions observed in Peru. Proceeding farther westward such an explanation becomes less adequate, and a period of general lower rainfall is probably implied by the data.

It is naturally of importance to inquire whether the phosphatic deposits of other regions give indications of equivalent changes.

The occurrence of phosphatic deposits under a plant cover, and without a large contemporary bird colony, is strongly suggested by the available accounts of the islands of the China Sea, notably all of those of the Dangerous Ground except Spratly Island, and Woody Island, if not other members of the Paracel group. An adequate interpretation of this region is, however, impossible without more ornithological information.

The islands of the western parts of the Indian Ocean may perhaps provide cases that are comparable. Fryer thought that the phosphate deposits were far more extensive than would be expected from modern bird colonies. It is, however, difficult to distinguish between ancient phosphatic rock, probably of Pleistocene age, as is certainly found on Aldabra, and more recent though not contemporary phosphatic guano which probably was present on many of the islands. The account of the phosphate of San Juan de Nova strongly suggests that it was formed by a relatively recent but not contemporary bird colony.

In the Caribbean and Cayman seas there appear to be similar indefinite indications of old post-Pleistocene deposits not formed by contemporary colonies. The deposit on El Dorado Islet, Orchilla, and the little-known occurrence of guano on Vivorillo Cays and the Caxones seem to provide examples. It is difficult, in this region as in the western Indian Ocean, to distinguish Pleistocene from Recent phosphatization. The guano incorporated into the San Juan formation of Desecheo and similar deposits in other parts of the West Indies may ultimately turn out to be comparable to the post-Pleistocene guano on vegetated atolls in the Pacific.

These few instances, unsatisfactory though they be, do at least suggest that the occurrence of buried post-Pleistocene guano may be expected in favorable regions throughout the tropics. If the phenomenon is really as widespread as it would appear to be, it suggests that it must be explained in terms of general planetary changes in precipitation rather than by purely local events. At present it is obviously not possible to go further in interpretation; the work of preparing the present survey will be justified if these tentative results stimulate an interest in what is

now left of the deposits and lead to the recording of information that might bear on the solution of the problem, before such information is irrevocably lost.

PHOSPHATIC DEPOSITS OF ELEVATED ISLANDS

The largest insular deposits occur on uplifted islands of coral rock or with a considerable veneer of coral limestone. They are found irregularly distributed in tropical and subtropical latitudes, the full list of occurrences of this sort being as follows:

Pacific Ocean:

Makatea, with small deposits on Niau, Matahiva, Henderson Island, etc.

Ocean Island and Nauru

Fais

Angaur and Peleliu

Rota, Saipan, Tinian, Aguijan

Kita and Okino Daito Jima

Smaller deposits on the Riu Kiu Islands

Ajawi

Walpole Island

Indian Ocean

Christmas Island

Aldabra (status of other islands obscure)

Caribbean

Navassa

Sombrero

Curaçao

Aruba

Bonaire

The Saldanha Bay and Langebaan Road deposits in South Africa may well be comparable to these insular localities, and certain very large deposits due to the phosphatization of igneous rock on the volcanic islands of Redonda, Alta Vela, and Gran Roque may be equivalent chronologically.

Omitting these special cases, the whole of the series listed above have certain common characters.

The phosphate lies in the cavities of a strongly developed Karrenfeld cut in the elevated coral limestone. Where the latter has been analyzed it has been found to be dolomitized. This is certainly the case for Makatea, Ocean Island, Nauru, Kita Daito Jima, and Christmas Island, Indian Ocean. No other cases have been discussed.

Dolomitization of reef limestone occurs unassociated with phosphatic deposits on

other islands in the Pacific, and it is quite likely that some cases of undolomitized elevated reef rock bearing phosphate will be discovered. It can, however, hardly be accidental that the five largest deposits rest on dolomite. Fryer's account of Aldabra indicates strong metamorphism of the reef rock bearing the phosphate which suggests that this locality is also dolomitized. It is impossible to gain any idea of the magnesium content of the reef rock of any of the other localities.

The phosphatic filling of the cavities in the Karrenfeld appears to vary most notably in its iron and aluminum content.

PACIFIC ISLANDS	(Al,Fe) ₂ O ₃	MEAN
Makatea	0.40- 0.92%	0.64%
Ocean	0.20- 0.70	0.45
Nauru	0.30- 0.53	0.40
Fais	1.53- 2.17	1.77
Angaur	1.57- 2.70	2.05
Peleliu	2.22-15.49	8.56
Eil Malk (nodular)	4.27-18.31	11.29
Urukthapel	13.97-24.40	19.19
Rota	1.12-12.08	6.28
Saipan	1.35-29.67	13.10
Tinian	0.86-28.02	13.51
Aguijan	no data	18.00
Okino Daito Jima	tr. - 6.08 or higher	3.29
Kita Daito Jima	(mainly aluminum phosphate)	
Yoron Shima	3.87-31.00	11.65
Tori Shima		9.6
Miyako Jima (excluding cave)	2.03-18.61	8.16
Hateruma Jima	3.8- 9.6	5.71
Walpole Island	no data	19.29

Analyses of the sesquioxides have been given for the underlying dolomitic limestone of two of the extreme cases, namely, for that of Nauru which contains 0.27% to 0.46% (Al,Fe)₂O₃ and for that of Kita Daito Jima which contains 0.08% to 0.78% (Al,Fe)₂O₃. The differences between these limestones, in this respect, is evidently negligible. Excluding that part of Kita Daito Jima that has received pumice from an external source, the spaces of the entire Karrenfeld are filled with a terra rossa-like clay which is presumably the residuum left on solution of the limestone. On Nauru nothing of this kind is found. Makatea and Ocean Island resemble Nauru in this respect. The other

islands all show more sesquioxides in their phosphate, and in some cases a typical terra rossa appears to exist. While it is probable that climatic factors and the proximity to rock other than limestone are involved, one factor of considerable importance in explaining the difference between Makatea, Ocean Island, and Nauru on the one hand and the other islands on the other is that these three islands appear to have undergone submergence since the formation of the Karrenfeld. Owen's observation of coral heads attached to pinnacles on Ocean Island is definite evidence in this direction. On Nauru strand lines appear to be cut on pinnacles, and the form of the deposit on Makatea is hard to reconcile with any other hypothesis. The history of these three islands is therefore rather different from that of the Mariana or Daito Islands. Angaur may perhaps have been partially submerged since the Karrenfeld was formed, but this island requires further study.

Outside the Pacific region, Christmas Island appears to have had a history like that of Makatea, Ocean Island, and Nauru, in that residual clay did not accumulate or was not left in the Karrenfeld, but where volcanic rock was exposed to guano solutions it was phosphatized on this island as on others.

In the West Indies, the history of Sombrero is too complex and too inadequately known to make comparison profitable. The upper part of Navassa appears to be comparable to the western Pacific islands. The phosphatic filling of the Karrenfeld on its plateau is rich in sesquioxides, while the deposit in the Karrenfeld of the low terrace around the island is lower in iron and aluminum as if part of the residual filling had been removed by wave action, possibly at a time of slightly higher sea levels than are now prevalent.

The situation at Curaçao is not entirely clear. The phosphate appears to lie on Molen-graaf's terrace at 90 to 110 meters. Subsequent to the formation of the terraces by emergence, subsidence to 100 meters is said to have occurred. This may have permitted loss of residual soil, though the Curaçao phosphate is slightly richer in sesquioxides than is that of Makatea, Ocean Island, or Nauru.

Summarizing the above argument, it seems likely that the elevated phosphatic islands can be classified as:

Islands not submerged after the Karrenfeld formations:

Fais
Angaur
Peleliu
Eil Malk
Urukthapel
Rota
Saipan
Tinian
Aguijan
Okino Daito Jima
Kita Daito Jima
Yoron Shima
Tori Shima
Miyako Jima
Hateruma Jima
Walpole Island
Navassa (in part)

Islands submerged after Karrenfeld formation¹ but prior to phosphatization:

Makatea
Ocean Island
Nauru
Christmas Island
Curaçao and adjacent islands

This difference is of some importance in providing a warning against the assumption of identical history for all such deposits.

Definite information on the age of the phosphate on the elevated islands, or even of that of the underlying limestone, is extremely meager. The dolomite of Makatea is supposedly fossiliferous and was regarded as Tertiary by Agassiz, though nothing critical was published. The Ocean Island dolomite yielded only a single *Carcharodon* tooth to Owen, and from this he deduced a post-Miocene age. Nauru yielded a number of supposedly Tertiary fossils to Elschner, but no detailed report on them seems to have appeared. The deposit on Kita Daito Jima lies on what is probably an early Pleistocene magnesian limestone.

If Tayama's classification of the terraces of the western Pacific islands is correct, the

¹ Rodgers (1948) believes the Karrenfeld forms beneath the soil surface, *pari passu* with phosphatization. All the comparative evidence from islands with exposed, unphosphatized pinnacles (Aldabra, Henderson Island, etc.) is against this view.

Fais, Peleliu, and possibly the Saipan phosphates rest on late Pleistocene raised reef rock or its equivalent. The deposit on Angaur apparently rests on somewhat older limestone. The deposits on Aguijan, Tinian, and Rota appear according to the same scheme to lie on Plio-Pleistocene Mariana reef rock, the Rota deposit perhaps on an older part of the Mariana formation than that underlying the other two.

The deposit on Miyako Jima contained an elephant molar, probably of middle or lower Pleistocene age, and rested on a limestone which is probably late Pliocene or early Pleistocene. On the adjacent Tarama Jima the deposits seem to have lain between Plio-Pleistocene and post-Pleistocene reefs.

The Christmas Island deposit lies on post-Miocene reef. The deposits on Bonaire, Curaçao, and Aruba appear to be Quaternary, though the evidence of a Pleistocene date is not entirely convincing.

The very meager evidence available thus suggests that the bed rock under all these deposits is either Pliocene or Pleistocene. No contradiction arises from the hypothesis that all the immense elevated deposits of phosphate are themselves actually of Pleistocene age, and this is confirmed by the one case of a mammalian fossil found in the phosphate. The evidence, notably from Tayama's work, seems to suggest at least two phases of phosphatization, one in the earlier and one in the later Pleistocene. There is, however, nothing to indicate that each island was not phosphatized at a different time. The periods of phosphatization evidently represent phases of comparatively short duration during the complicated Plio-Pleistocene history of the islands. The Saldanha Bay deposits of barrandite, or some like mineral, are, as has been indicated, probably comparable to the large elevated insular deposits. In this case there is reasonably good evidence for the association of the phosphatization with a Middle Pleistocene high sea level.

In the attempt to elucidate the meaning of these Plio-Pleistocene periods of phosphatization, it is first desirable to ascertain something of the probable rate at which the deposit on the richest islands could have been laid down.

If the area of the phosphatized region of Nauru be taken as 18 km² and the original reserve as 87,500,000 tons containing 38.99% P₂O₅ or 17.02% P, the mean phosphorus deposited on unit area is found to be 82.9 grams per cm². The total quantity of phosphatic guano on Howland Island has been estimated from two apparently independent sources as about 124,000 tons containing 14.9% P. The area of the island is 1.62 km², but it is evident from the existing accounts that not the entire area was phosphatized. If we assume that the phosphatized area was half the area of the island, as seems probable, the amount of phosphorus per unit area is 2.39 grams per cm². This comparison suggests that if the conditions on Nauru were comparable to those on Howland today, it would take about 35 times as long to phosphatize Nauru as was taken to produce the existing deposit on Howland.

The time of the beginning of phosphatization on Howland is uncertain. In its present form the island clearly dates from some post-Pleistocene time. The most recent event in the Pacific Basin that might have influenced phosphate deposition on the drier Line Islands would seem to have been the change responsible for the shift in guano deposition on the South American coast, probably in the first millennium B.C. It is therefore probably safe to conclude that the Howland deposit has been accumulating for at least 2500 years. This would imply a minimum time of 87,500 years to produce the Nauru deposit. It is, however, most unlikely that an island of the size of Nauru could have accumulated its deposit in this time under the existing oceanographic and climatic regime of Howland. The Howland bird colony may have originally covered the whole area within the rampart. The colony on the much larger Malden Island certainly did not. The total guano production from Malden Island seems to have been about four times that of Howland, but its area is approximately 20 times that of the latter island. It is reasonable to suppose that as the size of the island increases the bird colony does not increase proportionately because increase in size of an island will not increase the food available in the adjacent waters within the cruising radius of breeding birds.

If under existing conditions a colony of birds four times that present on Howland represents the upper limit then it would have taken at least

$$\frac{87,500,000}{4 \times 124,000} = 490,000 \text{ years}$$

to phosphatize Nauru. This is a very considerable fraction, of the order of magnitude of one-half, of Pleistocene time. Even if the phosphate deposit on Baker Island, which is less well known than that on Howland but may have been three times as great, be taken as a standard, the time of phosphatization would be 160,000 years or about one-sixth of Pleistocene time. In view of the rather critical conditions that have evidently been necessary to produce deposits on atolls of over 100,000 tons during post-Pleistocene time, it is extremely improbable that there would have been time enough during so changeable a period as the Pleistocene for the Nauru deposit to develop under oceanographic and climatic conditions at present represented by Baker and Howland Islands. Such an argument is in accord with the strong impression left by Tayama's results, of a complex history, only short sections of which were characterized by intense phosphatization.

If we compare the Nauru deposit with that on the Peruvian islands an entirely different result is obtained.

The present rate of deposition on the best Peruvian sites is 9.6 grams per cm² per year. This material contains 4.59% P, so that 0.44 grams P per cm² per year can apparently be deposited under the most favorable conditions. Assuming no loss the Nauru deposit would at this rate have taken just under 200 years to form. It has, however, already been pointed out that losses did occur from the Peruvian deposits. On North Chincha Island the mean depth of the guano was 12.6 meters. Assuming a density of 0.9 and a phosphorus content of 5.28% this corresponds to 59.9 grams of phosphorus, or just under three-fourths the quantity present per unit area on Nauru. Since the Chincha deposit appears to have taken between 2000 and 3000 years to form, at the same rate the Nauru deposit would have taken about 3000 to 4000 years to form.

The argument of the preceding paragraph may be summarized by the statement that while under existing equatorial Pacific conditions at their most favorable the Nauru deposit would have required hundreds of thousands of years for formation, under existing Peruvian conditions it would have been deposited in a few thousand years. The extremely long period, in view of the critical nature of the conditions for phosphatization, is most unlikely. It is much more probable that conditions have changed and that the Nauru deposit reflects a time when the central Pacific had a lower rainfall and also was much more biologically productive than it is today.

Any kind of change enhancing the productivity of the central part of the largest oceanic basins is likely to act on the greater part of the rest of the ocean. Such a hypothesis therefore explains the curious fact that whereas in recent times massive deposits of the order of millions of tons of guano are known to have accumulated only on islands in the most fertile coastal region of the world, such large accumulations were of tropicopolitan distribution during the Pleistocene and occurred in strictly oceanic localities. The hypothesis, which was erected on the basis of what may appear to be a somewhat tenuous calculation grounded in unsupported assumptions, is greatly strengthened by the fact that an increase in the fertility of the oceans during interglacial periods is not unexpected on general grounds.

Dr. E. F. Thompson, in the course of a discussion of certain problems of marine zoogeography, has pointed out to me that if the polar ice caps were to disappear, the entire thermal structure of the oceans would be altered. With the much less steep thermal gradient from Equator to pole the areas that could provide cold deep and intermediate water would be immensely reduced, and no water so cold as that at present sinking in the Antarctic Ocean would be likely to be present. The result of this process would be a far gentler vertical as well as horizontal thermal gradient. In consequence the over-all resistance to vertical mixing in the oceans would be reduced and, where upwelling occurred, the rising water might be expected to come

from greater depths. Phosphate and nitrogen compounds stored in the depths of the ocean would be more accessible than they are today, and the illuminated zone of the ocean would be correspondingly more productive.

It is probable that complete disappearance of the polar caps would not be needed to produce significant changes in the temperature distributions in the tropical oceans. A restricted continental ice cap on the interior of the Antarctic continent could hardly have the same effect on the Antarctic Ocean as the pack-ice of today. Any change that increased the temperature of the intermediate water masses would be likely to increase productivity at the surface, and it is not unlikely that productivity would be greatest during the periods of declining glaciation when nutrients stored up during a long prior period were being released to the upper layers. This argument strongly suggests that the interglacials, or at least the first half of each interglacial, should correspond to periods of enhanced oceanic productivity.

It must, however, be admitted that Dr. G. A. Riley, with whom I have also discussed the matter, believes that glacial rather than interglacial periods would be likely to be times of enhanced productivity. Further research is evidently needed; what is important is that variation in productivity during the Pleistocene is quite likely.

One further aspect of this matter may be briefly explored. Although a considerable number of methods for the synthesis of dolomite have been published, the only observations that bear on the method of dolomite formation under conditions likely to occur in the surface waters of the oceans are those of Rivière (1939a, 1939b). According to this author the partial replacement of calcium in calcareous sediments by magnesium from sea water is facilitated by a slight increase in pH, such as may occur as the result of loss of CO₂ to the air or in photosynthesis. It is therefore not impossible that the dolomitization taking place prior to phosphatization is also to be regarded as evidence of a somewhat greater local productivity on the emergent dying reefs than would usually be expected in the open ocean.

CAVE GUANO

A NUMBER OF DEPOSITS of fecal origin are known in caves. Such deposits are usually produced by bats, but a few cases are known in which other mammals or, more rarely, birds have inhabited caves in sufficient numbers to produce deposits of significance. When the chemistry of such deposits is considered the diversity in the feeding habits of the animals producing them must be borne in mind. Most of the Microchiroptera, which alone among the bats have produced cave guano, are insectivorous, but a few species, notably of the genus *Artibeus*, devour fruit, and some cave guano in the West Indies may be deposited by the fish-eating bat *Noctilio*. The few rodents and ungulates that have produced guano are, of course, herbivorous, while bears favor a mixed diet. Cave-inhabiting birds that have produced or augmented the coprogenic deposits of caves have very varied diets, *Collocalia* feeding on insects, *Steatornis* on fruit, and the European rock dove having a rather mixed diet.

Most of the important deposits to be considered have certainly been produced by bats. There are a few analyses of relatively fresh bat dung.

	I	II	III
Ignitable matter	93.75%	83.65%	82.63%
Total nitrogen	8.25	10.25	11.73
CaO	—	2.36	4.56
MgO	—	1.40	1.03
K ₂ O	—	3.85	1.57
Al ₂ O ₃	—	0.00	0.49
Fe ₂ O ₃	—	0.38	0.78
P ₂ O ₅	2.25	6.95	7.42
SO ₃	—	3.00	3.80
Insol.	—	0.16	1.39

- I. Droppings of *Rhinolophus hipposideros* (Popp, 1871).
- II. Fresh bat guano, Lares, Puerto Rico.
- III. Fresh bat guano, San Germán, Puerto Rico (Gile and Carrero, 1918).

The first analysis may represent the only reasonably undecomposed specimen for which an analysis is recorded. The P₂O₅ here constitutes 36% of the ash, while in II and III it represents 42.3% and 42.6% of the ash, respectively. These three figures are sufficiently concordant to suggest that in general the P₂O₅ content is over a third of the

unignitable material. When CaO is determined, it appears to be present in quantities less than are required to produce even CaHPO₄. Schadler (1931), without giving authorities or analytical detail, states that fresh bat guano contains 0.5% to 1.5% P₂O₅ not combined with calcium. This is probably concordant with Popp's analysis. In I, the nitrogen is 9.34% of the ignitable matter, a not unreasonable figure if one supposes that the organic fraction consisted of a mixture of chitin and arthropodin. In II and III the nitrogen constitutes 12.25% and 14.19% of the ignitable matter. Either some exoskeletal matter has been decomposed and the ammonia retained, or nitrogen has been added from the urine. Initially the urinary nitrogen would be present mostly as urea, but decomposition to ammonium carbonate would doubtless be very rapid. There is, however, evidence, to be given later, that sometimes bats micturate and defecate in such a way that the products are not immediately mixed, the feces falling onto the floor of the cave, the urine spraying the wall. One extraordinary case of fairly pure urea collecting as a mineral on the wall of a cave in Egypt has in fact been described.

Bat guano is known from most of the cave districts of warm temperate and tropical regions. In addition to the countries specifically discussed below there are vague references to deposits in Colombia and Turkey (Paris, 1899). The largest deposits at present occupy caves in tropical or subtropical countries, but equally large deposits were evidently formed in Europe, notably during the last (Riss-Würm) interglacial, at a time which, though perhaps slightly warmer than the present, was certainly not subtropical. The term chiropterite, introduced as a rock name for the phosphatic earth of the Drachenhöhle, Mixnitz, Austria, is conveniently applied to such ancient guano.

In addition to the caves to be discussed below, various occurrences of coprolites in caves have been recorded but without a clear indication that a definite stratum or accumulation of fecal matter had occurred. In order to set a convenient limit to the present work, isolated coprolites are not considered. It

is, however, desirable to call attention to the figures of the subfossil feces of *Glossotherium*, from the famous Eberhardt Cave, Last Hope Inlet, Patagonia, which have been figured by Roth (1899) and which may be compared with the dung of the North American *Nothro-*

therium which certainly occurs as true guano deposits. It is indeed conceivable that the *Glossotherium* material described as "una gran cantidad de estiércol pisoteado y en parte pulverizado" should be included as a true aggregate.

CAVE GUANO IN SOUTH AND CENTRAL AMERICA

URUGUAY

Schroeder (1915) has given an analysis (I) of a bat guano from the cave Cerro de Arequita near Montevideo. The deposit is said to have consisted of a brownish black material, fairly dry at the surface and very wet in the lower layers. A second sample (II) submitted to him is referred doubtfully to the same locality. The deposit is said to have been small. The analyses were made on material dried at 50° C.

	I	II
H ₂ O	12.96%	10.80%
Ash	76.22	74.00
N total	5.59	6.93
P ₂ O ₅ total	7.45	5.54
CaO	1.20	1.40
K ₂ O	3.14	2.78

Most of the material is evidently not of coprogenic origin. In view of the small amount of organic matter present, apparently not more than 10.82% in the first sample and 15.20% in the second, the nitrogen was presumably present as nitrate.

The large quantity of nitrogen in relation to phosphate suggests that enrichment, perhaps by the upward capillary movement of water containing nitrate, must have taken place.

BRAZIL

Eschwege (1833) in a work on the mineral resources of Brazil describes the manufacture of saltpeter from the cave earth of caverns of Monte Rorigo, Mirelles, Formiga, in the Serro do Frio, and Formiga, Comarca, Rio dos Mortes. He visited the two last-named localities. The cavern in the Serro do Frio was worked out in 1818, but contained a large population of bats. The cavern at Formiga, Comarca, Rio dos Mortes, is said to have had stalactites and an underground stream, evidently with a variable water level. The

cave floor bore cave earth which filled the innermost recesses completely and in part formed a conglomerate with quartz and iron-stone pebbles. The upper 2.4 meters (10 palmen) of the deposit was impregnated with salts and from it nitrate could be obtained. The deposit containing the nitrate apparently all lay about 24 meters above the level of the underground stream. Eschwege realized that these deposits, which were doubtless rich in phosphate as well as nitrate, were derived from bat guano.

Branner (1919) states that niter caves occur in all the states of Brazil, notably in Ceara, Pernambuco, Bahia, Espirito Santo, Minas Gerais, and Matto Grosso.

A considerable number of bat bones have been found in the caves of Lagoa Santa, Minas Gerais, associated with a rich terrestrial mammalian fauna, in part extinct (Reinhardt, 1888; Winge, 1893). There does not seem, however, to be any indication of large chiropterite deposits in these caves.

VENEZUELA

Data mainly relating to the nitrate in cave earth have been published by Muntz and Marcano (1887). It is probable that bat guano is usually the source of the nitrate, but other Venezuelan caves with remarkable bird colonies are known. The localities discussed by Muntz and Marcano are listed by the names given in their paper, which have clearly become gallicized in some instances.

LA MARGUERITE, LA MIEL

This cave is situated near the summit of a calcareous hill 160 meters high rising from the plain of Araure, at the northeastern end of the Cordillera de Merida. The cave consists of several galleries running at least 100 meters into the long axis of the hill. It is inhabited by bats and contains up to 5 meters of cave

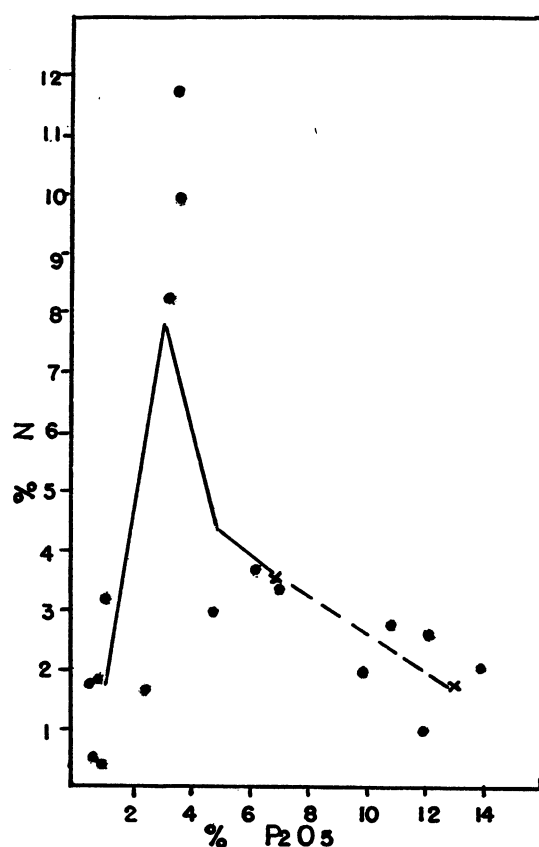


FIG. 78. Relationship of total nitrogen to phosphate in Venezuelan guanos.

earth. Muntz and Marcano give the following analyses:

	CAVE EARTH, INTERIOR OF CAVERN	CAVE EARTH AT EN- TRANCE	EARTH OUTSIDE AT SOME DISTANCE FROM EN- TRANCE
Organic N	11.74%	2.41%	0.80%
N·NO ₃	0.00	3.03	10.36
P ₂ O ₅	3.68	1.15	6.10

They consider that the very high nitrate of the soil outside the cave is due to nitrification of the organic nitrogen of the cave earth and subsequent migration in the soil from the cave outward into the surrounding terrain.

LA CORDILLERE

Six caverns with this designation, which may refer to the Cordillera de Merida, contained a considerable amount of cave earth. The purest material was pulverulent and

smelt of ammonia; it was formed largely of insect debris, elytra, legs, and the scales of lepidopterous wings. Bat bones were found in this material. Analyses gave:

H ₂ O (moisture)	18.5 %
Organic and ammonium salts	72.40
Nitrogen	9.84
Total ash	9.10
P ₂ O ₅	3.68

This material was at least 1 meter thick. In places alternate layers of such a deposit and a cave earth very rich in nitrate were encountered, suggesting that periods of accumulation of guano alternated with periods of nitrification.

Outside the caves the soil contained a variable amount of nitrate; in places a schist lay beneath the nitrate-containing earth and was apparently being attacked by the nitrate. An average sample of the material from outside the cave gave:

H ₂ O (moisture)	13.8 %
CaO water sol.	10.10
CaO insol.	16.66
MgO	tr.
N ₂ O ₅ water sol.	7.20
N org.	2.43
P ₂ O ₅ water sol.	0.11
P ₂ O ₅ water insol.	16.80
SO ₃	0.85
Cl	0.10
CO ₂	absent

It is evident that considerable amounts of nitrocalcite and calcium phosphate existed in this soil. The organic matter of this material gave a yellow solution in water from which it could be partially precipitated by acid. A number of less complete analyses of earths from in or near these caves are given; these have been used in constructing figure 78.

ISLE OF TOAS

LATITUDE 10° 57' N., LONGITUDE 71° 42' W.

A locality at the base of the Cordillera described, perhaps by error, under the general heading of the Isle of Toas supplied two specimens, one (I) from the center of the mass of cave earth, the other (II) from the surface at the entrance. The description suggests that these specimens actually did not come from the island.

	I	II
H ₂ O (moisture)	25.5 %	32.12%
N ₂ O ₅	5.40	4.08
N organic	0.60	1.73
P ₂ O ₅	13.95	10.80
CaSO ₄	14.34	12.43

The island, which lies at the entrance of the Lake of Maracaibo in latitude 10° 57' N., longitude 71° 42' W., is described as having caves in the calcareous range of hills on its east-northeast coast. These caves contained a layer of cave earth inclined at an angle of 15° to the horizontal and running back into the interior of the caverns. Two caves were explored, El Morro and El Olivo. Samples I and II came from the former, the first being superficial, the second from 2.3 meters. Samples IV and V came from El Olivo, the first being superficial, the second from a depth of 1 meter. The provenance of sample III is not given.

	I	II
H ₂ O (moisture)	—	21.60%
N ₂ O ₅	7.63%	4.90
N organic	3.70	1.32
P ₂ O ₅	5.76	12.10

LOS MORROS DE SAN JUAN

On the south side of Lake Valencia, between Villa de Cura and San Juan, with caverns from which cave earth was obtained which contained N₂O₅ 1.9%, P₂O₅ 0.66%. This material evidently contained little guano, and even poorer specimens were collected in caves at El Encantado, 2 leagues east of Caracas.

VILLA DE CURA

A cave earth contained organic nitrogen 1.6%, P₂O₅ 13.7%, and a considerable but undetermined amount of nitrate.

PARAPARA

South of the above locality. Earth from a small cavern contained but N₂O₅ 1.30% and P₂O₅ 0.95%, but outside the cave soils containing up to N₂O₅ 4.4% and P₂O₅ 14.85% were collected.

MARACAIBO

On the south side of Lake Valencia (a locality that it has not been possible to identify). A bat guano covering nitrated earth, formed principally of the elytra of insects, contained in a dry state:

N organic	7.9 %
N ₂ O ₅	1.15
P ₂ O ₅	3.3

In addition to these localities it would appear probable from von Humboldt's (1817) account that much of the cave earth of the celebrated Guacharo Caves, Caripe Cumaná, Venezuela, is formed from the egested remains of fruit seeds deposited by the oil bird, *Steatornis caripensis* Humboldt.

III	IV	V
—	—	—
1.94%	4.56%	2.12%
1.17	0.78	0.44
2.50	9.83	11.90

HONDURAS

CUEVA LAS PIEDRAS, COMAYAGUA

Taylor (1858) records the crystalline mineral lecontite from a black bituminous mass formed from the excreta of bats in this cave. The cave earth at the entrance of the cavern was used as a source of niter. Lecontite gave on analysis:

H ₂ O	19.45%
Na ₂ O	17.56
(NH ₄) ₂ O	12.94
K ₂ O	2.67
SO ₃	44.97
Organic	2.30
Inorganic residue	0.11

The mineral is evidently a hydrated ammonium sodium sulphate, (Na,NH₄,K)₂SO₄·2H₂O; the equivalent ammonium potassium sulphate is known from Réunion. It is probable that many other caves containing bat guano occur in Central America but have not been recorded.

CAVE GUANO IN THE ANTILLES

PUERTO RICO

A large number of caves containing bat guano are known in the island of Puerto Rico. It is probable, from Anthony's (1925) account, that nearly all of this guano is produced by *Tadarida murina* (Gray). Of the 11 living species of bats recorded by Anthony (1925) as inhabiting the island, 10 may occur in caves, only *Molossus fortis* Miller not living in such habitats. None of these species, however, is as likely to produce massive quantities of guano as is *T. murina*, though at times any of them may contribute something to the accumulation. Anthony indicates that in a shallow cave "Piedra de la Cueva," Old Loiza, near San Juan, a large pile of droppings had been produced by the very local fish-eating bat, *Noctilio leporinus mastivus* (Dahl). The guano attributed by Gile and Carrero (1918) to fruit-eating bats is doubtless produced by *Artibeus j. jamaicensis* Leach, a frugivorous species common throughout the island (Anthony, 1925).

The bat caves of Puerto Rico occur in limestones of various ages, mainly in the western and central sections of the island. The caves in the northwestern coastal area are in Tertiary limestones; those of the central region, notably south of Aguas Buenas and near Comerío, are in Mesozoic limestone (cf. Meyerhoff, 1933). Sixty-one caves are recorded by Gile and Carrero as containing significant quantities of guano. These caves lie in the following municipal districts:

North coastal Tertiary region:

Aguadilla (1), Moca (3), Isabela (5), Camuy (1), Lares (4), Hatillo (2), Arecibo (1), Manati (3), Ciales (1), Vega Baja (2), and apparently Morovis (13)

Central pre-Tertiary axis

Cabo Rojo (3), San Germán (4), Comerío (3), Aguas Buenas (3)

Southern coastal region (sites of caves relative to Tertiary deposits uncertain)

Guernica Central (3), Peñuelas (3), Juana Diaz (2)

In addition to these, the following localities have not been identified: Tierras Nuevas, Campo Alegre; Hacienda Juanita between Mayaguez and Las Marias; Santa Rita; La Majina, Limon. It is also evident from the

account given by Anthony that extensive caves near Utuado, in the central axis, have yielded much skeletal material from a cave earth which presumably contains bat guano.

The most important caves are certainly the group near Morovis, a locality which lies just at the northern border of the central axis and at the junction of the Arecibo formation (Tertiary), older sediments, and intrusive rocks. Semmes (1919) does not mention the caves near Morovis specifically, but it appears from his account that they are in the Tertiary formation.

The total quantity of guano present in the 61 caves listed by Gile and Carrero was estimated as 16,025 tons, the largest deposit being in the cave "Oscura" at Cabachuelas, Morovis.

Anthony has described many fossil bones from the Puerto Rican bat caves, notably from Morovis and Utuado. These bones were discovered at depths "from a few inches down to as deep as nine feet." The surface of the cave deposits examined by Anthony were, however, not always the original surfaces, as guano had been removed in a number of caves. The bones belong to four species of recent bats, to three species of fossil bats, only one of which, *Monophyllus frater* Anthony, is congeneric with an associated, still living species, namely, *M. portoricensis* Miller, with which it co-occurred in a cave near Morovis, and to an extraordinary assemblage of extinct, ground-living mammals. Bones of a number of species of birds also occur in these deposits, six species being extinct. The extinct and living species are not separated stratigraphically. Thus in Cueva Catedral, Morovis, the remarkable insectivore *Nesophontes edithae* Anthony was associated with the skulls of living species of bats. There is every reason to think that this remarkable extinct fauna inhabited Puerto Rico at least until European settlement. Some species of the extinct birds and bats may have survived into the last century (cf. Anthony, 1925; Wetmore, 1926).

A very large number of samples of Puerto Rican guano have been studied chemically by Gile and Carrero (1918). For nearly all specimens they give total phosphorus and

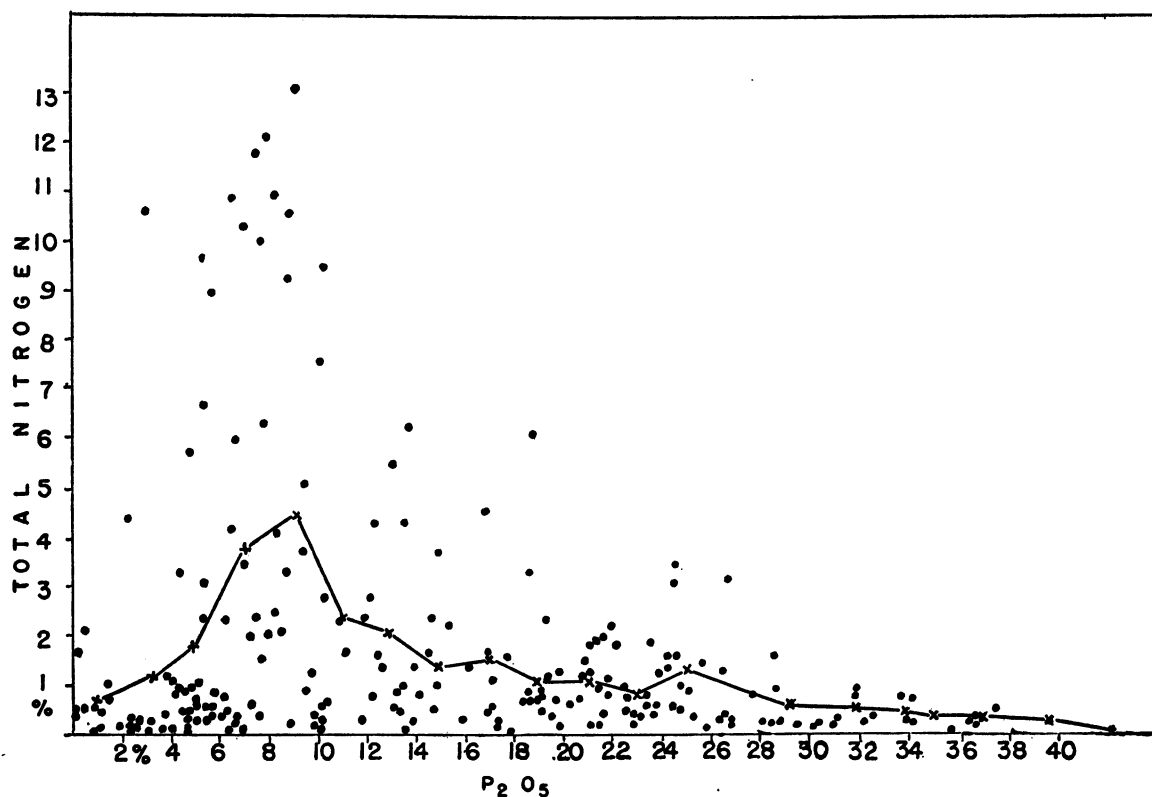


FIG. 79. Relationship of total nitrogen to phosphate in Puerto Rican cave guanos.

nitrogen; for most, citrate-soluble phosphorus; and for some, water-soluble phosphorus and nitric and ammonia nitrogen. The relationship of the total nitrogen to total P_2O_5 in the whole series of analyses is plotted in figure 79, the line being drawn to represent mean nitrogen contents by 2% classes of P_2O_5 . This line serves as a convenient standard for comparison with the nitrogen contents of bat guanos in other regions. The material containing very little nitrogen and phosphorus is doubtless much contaminated with cave earth of inorganic origin, that with much phosphate but little nitrogen is highly decomposed and leached guano, that with high nitrogen and moderate or low phosphate is clearly relatively undecomposed and uncontaminated guano.

The more complete analyses given by Gile and Carrero are set out in table 34.

The water-soluble phosphate is seen to be high in the two fully analyzed samples of fresh bat droppings, namely, Lares, 40.6%, and Francisco Quiñones, San Germán, 32.5%.

The citrate-soluble phosphate in these two specimens was very high, namely, 92.6% and 68.0%. In a third fresh sample, from Barrio Monte Grande, San Germán, 83.9% of the phosphate was citrate soluble, but water-soluble phosphate was not determined. In the older material the proportion of water-soluble phosphorus is nearly always low. In 53 analyses it ranged from 0% to 43.7% of the total phosphorus, but in only five cases was the amount recorded over 10% of the total, and all of these were relatively superficial samples containing at least 4.28% N. The proportion of citrate-soluble phosphate varies from 0% to 92.5% of the total phosphate. The higher proportions of citrate-soluble phosphate tend to occur in the lower part of the range of total phosphorus, suggesting that as the organic matter of the guano decomposes the phosphate tends to become less citrate soluble. The relationships of nitrate and ammonia nitrogen to total nitrogen indicate that considerable nitrification must take place early in decomposi-

TABLE 34

	Ign. Matter	Total N	Total P ₂ O ₅	P ₂ O ₅ Water Sol.	P ₂ O ₅ Cit. Sol.	K ₂ O Water Sol.	CaO	MgO	Fe ₂ O ₃	Al ₂ O ₃	SO ₃	Insol.
	%	%	%	%	%	%	%	%	%	%	%	%
Fresh, Lares	83.65	10.25	6.95	2.82	6.43	3.88	2.36	1.40	0.38	0.0	3.0	0.16
"Ancones" Barrio Ancones, San Germán:												
0-1 ft.	32.85	1.46	7.75	0.90	1.37	0.25	25.51	0	3.35	0.23	23.95	4.01
1-2 ft.	31.86	1.43	10.50	0.78	0.80	0.06	19.45	0	4.60	4.46	19.31	5.62
2-3 ft.	21.13	0.27	28.08	0.24	1.37	0.10	7.49	0	6.27	15.77	7.81	10.84
3-4 ft.	27.27	0.28	31.20	0.30	4.97	0.47	6.75	0	5.03	19.52	2.24	5.87
5-6 ft.	17.42	0.33	26.51	0.40	1.22	0.13	3.78	0	7.56	12.90	2.32	25.37
Black peaty, from pocket	46.38	5.35	13.06	0.39	2.08	0.31	13.12	0	5.97	2.00	1.46	16.97
Francisco Quiñones, San Germán:												
Fresh cave mouth	82.63	11.73	7.42	2.40	5.04	1.57	4.56	1.03	0.78	0.49	3.80	1.39
3-4 ft., mouth	24.30	0.80	19.04	0.19	3.94	0.28	8.18	0.57	8.46	8.44	5.56	23.68
6-7 ft., mouth	19.51	0.64	29.31	tr.	3.81	0.22	2.15	tr.	13.25	13.08	0	18.28
0-1 ft., near center	15.92	0.38	22.91	tr.	0	0.23	2.02	0	15.20	6.15	0	38.14
0-1 ft., different place near center	15.35	0.56	24.43	tr.	0	0.13	2.48	tr.	15.00	8.44	0	31.62
8-9 ft., different place near center	14.40	0.18	21.45	tr.	0	0.34	0.74	tr.	11.33	7.77	—	42.70
Gray-black, dusty, 0-1 ft., just out- side entrance	24.50	0.59	10.18	tr.	3.28	0.29	22.77	1.89	4.61	2.62	6.97	24.00
San Germán	38.69	1.32	13.85	0.51	5.29	0.77	5.24	0.05	4.33	2.89	17.10	14.53
Las Marias fruit- eating bat guano, mostly seeds	56.67	3.23	4.35	0.46	2.42	0.25	1.74	0.27	10.58	2.37	10.95	16.44
Las Marias	28.32	0.66	18.55	1.10	3.89	0.18	13.72	1.15	5.33	5.47	17.54	12.97
Cabo Rojo	26.29	0.66	20.73	0.41	1.13	0.23	15.18	0.17	5.17	8.61	2.80	17.83
Cabo Rojo	28.98	1.63	14.47	0.53	3.24	—	5.82	tr.	6.03	6.86	7.37	28.55
Hacienda Marga- reta, Cabo Rojo	32.30	0.97	13.56	0	6.85	0.32	19.86	0.20	5.34	3.65	5.98	20.01
Arecibo	22.02	0.52	12.68	0.82	2.96	0.96	22.45	0.20	4.27	4.44	19.54	16.68
Cayey	28.94	0.76	19.10	1.55	10.72	tr.	27.62	tr.	2.42	1.21	16.16	7.48
Cayey	27.72	0.84	18.30	1.04	8.11	tr.	21.19	tr.	4.28	3.37	10.42	16.11
Vega Baja	19.04	1.06	26.18	0.33	10.45	0.42	34.36	0.10	4.90	1.11	3.06	6.54
Aguadilla, mixed lot with CaCO ₃	27.64	0.40	7.77	0.28	2.92	0.64	30.49	tr.	3.04	0.33	18.97	8.94

TABLE 35

Centimeters (Feet in Parentheses)	Water- insoluble P ₂ O ₅	CaO	Fe ₂ O ₃	Al ₂ O ₃	SO ₃	Excess of Bases over Acids
0-30.5 (0-1)	144.6	910.0	63.0	6.7	100.1	665.3
30.5-61 (1-2)	205.2	693.0	86.4	131.1	141.0	347.8
61-91.5 (2-3)	588.0	266.8	57.9	464.1	191.1	9.7
91.5-122 (3-4)	653.1	240.4	95.1	574.5	252.5	4.4
152.5-183 (5-6)	552.0	134.8	141.9	579.8	132.2	172.3

tion. The high proportions of ammonia are all in the upper part of the range of total nitrogen contents, while a high proportion of nitrate can apparently occur at any total nitrogen concentration.

The profile from the cave Ancones, San Germán, is the most complete, not only of the Puerto Rican series but of any post-Pleistocene bat cave. The water-insoluble material and sulphate can be conveniently considered in terms of milli-equivalents per 100 grams, as in table 35. It is immediately

able quantity of organic matter containing about as much nitrogen as does chitin was present. Such material is definitely less rich in nitrogen than is the volatile matter of the fresh guano of the first two analyses of table 34, which contain 12.2% and 14.2% N, respectively. It seems likely that ammonia from urine and protein in the feces are first decomposed, that chitin and scleroprotein of the insect exoskeleton are then more slowly destroyed, and that the final organic material is low in nitrogen.

TABLE 36

Centimeters	(1) Volatile Matter	(2) CO ₂ in CaCO ₃	(3) Volatile Matter Less CO ₂	(4) N Total	(5) % N in (3)
0-30.5	32.85%	14.62%	17.83%	1.46%	8.2%
30.5-61	31.86	7.65	24.21	1.43	5.9
61-91.5	21.13	0.22	20.91	0.27	1.3
91.5-122	27.27	0.10	27.17	0.28	1.0 ^a

^a If all the aluminum and iron of this sample be regarded as (Al, Fe)PO₄·2H₂O, 7.5% essential H₂O would be present and the nitrogen content of the volatile matter less this water would be 1.4%.

apparent that there is an excess of calcium over phosphate at the top of the profile, while in the lower part an appreciable amount of the phosphate must be present as aluminum or ferric phosphate. If it may be assumed that the sulphate in the profile is all present as CaSO₄, virtually the whole of the sesquioxides in the 2-3- and 3-4-foot samples would be present as (Al, Fe)PO₄. The high excess of bases at the bottom of the profile is obviously due to sesquioxides either free or as easily decomposed soil minerals. In general it is evident that in the upper part of the profile most or all of the phosphate is likely to have been present as a calcium phosphate; in the lower part a large amount is present as ferric and aluminum phosphate. Moreover, there is a definite enrichment of aluminum over iron in the lower region, suggesting that aluminum has migrated downward as phosphate.

If we may assume that the excess of bases in the four upper samples represents calcium carbonate, the equivalent CO₂ can be computed as in table 36. The results in column 5 suggest that in the upper layers a consider-

HISPANIOLA (HAITI AND SANTO DOMINGO)

Numerous caves that contained deposits very like those of Puerto Rico undoubtedly exist in Haiti and Santo Domingo, but little has been written of them.

C. F. Miller (1914) indicates that a cave at El Fondo, Santo Domingo, contained 700 tons of guano and that the deposit was formed by a contemporary bat colony, which when it issued from the cave formed a column of cross section as great as an ordinary street car (i.e., at least 6 m²) which took an hour to pass. The material analyzed was obviously very fresh, containing 90% volatile matter, 11.84% N, 4.80% P₂O₅, and 1.61% K₂O.

Poole (1929) records guano caves at L'Atalaye, about 250 kilometers north of Port-au-Prince, near St. Michel, about 5 kilometers west of L'Atalaye, and near San Rafael, about 24 kilometers north of the last-named place.

Miller and Krieger (1929) discuss caves that had been worked for guano in Samaná Province, Santo Domingo, and from these Miller (1929) records a rich mammalian fauna, including species of *Nesophontes* and

Isolobodon, recalling the Puerto Rican localities already discussed. The mammalian remains were evidently in large part derived from the pellets ejected by *Tyto ostologus* Wetmore, an enormous owl which apparently became extinct in the eighteenth century (Wetmore and Swales, 1931). The only bats recorded from the Samaná caves were *Eptesicus hispaniolae* Miller, *Macrotus w. waterhousii* Gray, and *Artibeus j. jamaicensis*, all of which still inhabit the island.

CUBA

A considerable amount of bat guano has been obtained in Cuba (Crawley, 1908; Agéton, 1915), but few detailed accounts of its occurrence are available. In its mode of occurrence and composition Cuban bat guano is clearly comparable to that of Puerto Rico. Anthony (1919) describes one cave, the Cueva de los Indios, near Daiquiri, not to be confused with the cave El Indio at the western end of the island described by Agéton (1917), as containing dark brown earth, loose and light in texture, formed from decomposed bat guano and limestone. This cave, about 50 meters long, has a partially collapsed roof and resembles the Cueva Catedral at Morovis in Puerto Rico. Much material seems to have been washed out of the Cueva de los Indios, but a low rounded bank of earth about 13 meters long and 8 inches wide probably represented an old guano pile of great size. In the upper part of this mound innumerable mammalian bones occurred. On the surface these were partly of recent bats of the genus *Artibeus*, with modern rat bones, but even superficially some old and very dark bones occurred, as if some agency had removed the original surface of the mound and left exposed fossil remains mixed with recent bones. The bones are largely those of bats, the commonest species being apparently *Brachyphylla nana* Miller, *Artibeus jamaicensis parvipes* (Rehn), *Phyllops vetus* Anthony, and *Phyllonycteris poeyi* Gundlach. The insectivore *Nesophontes micrus* G. M. Allen and the rodents *Capromys nana*, *Geocapromys columbianus* (Chapman), and *Boromys torrei* G. M. Allen were associated with the bat bones. It is interesting that no evidence of either recent or fossil *Tadarida* was encountered around Daiquiri, though two

species, *T. murina* (Gray) and *T. macrotis* (Gray), are known from the island.

Petermann (1888) analyzed two Cuban samples, finding:

N total	8 %	2 %
P ₂ O ₅ total	6.2	11.8
K ₂ O	1.0	1.7

A third sample is said to have consisted largely of potassium sulphate.

A number of partial analyses of Cuban bat guanos have been published by Crawley, and Agéton adds two more. In a later paper

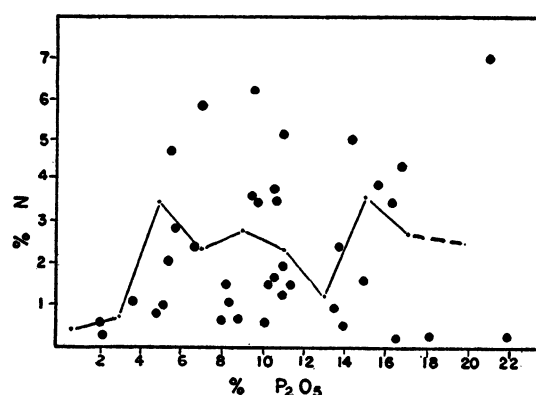


FIG. 80. Relationship of total nitrogen to phosphate in Cuban cave guanos.

Agéton (1917) gives many analyses, all related to material dried at 100° C. and so not comparable to those from other localities. In general the distribution of the total nitrogen related to phosphates (fig. 80) is similar to that of Puerto Rican specimens. The mean and extreme values of the determinations made by Crawley are:

	EXTREMES	MEANS
P ₂ O ₅ total	0.80–21.85%	8.60%
P ₂ O ₅ water sol.	0.11– 3.19	1.58
P ₂ O ₅ citric sol.*	1.01– 6.96	2.96
N total	0.21– 7.13	2.37
N·NH ₃	0.01– 3.40	0.89
N·NO ₃	0.01– 2.05	0.49
N·organic	0.11– 6.81	1.93
K ₂ O	0.03– 8.83	1.55
Na ₂ O (3 analyses)	0.26– 1.70	
CaO	0.53–22.05	
Cl (5 analyses)	0.14– 0.44	
H ₂ O (moisture)	1.64–36.44	

* "Available" less "water sol."

Agéton's numerous analyses relate mainly to caves at the western end of the island.

EL INDIO, 7 KILOMETERS NORTH OF
BACUNAGUA, PINAR DEL RIO

A large and complex cave described by Agéton, who gives a map. The distance from the entrance to the farthest recess is 1180 meters. Part of the surface of the cave earth is covered with a layer of calcium sulphate, up to 37 cm. thick. In other parts of the cave the deposit appears stratified or may contain buried crusts and pockets of calcium sulphate. The thickness of the phosphatic cave earth in places reached 4.6 meters (15 feet). Fifty partial analyses, based on material dried at 100° C. and representing the means of one or more complete profiles, are given. The mean ranges and means of the constituents determined were as follows:

	RANGES	MEANS
P ₂ O ₅ total	11.7- 28.5 %	19.7%
P ₂ O ₅ assimilable (pre- sumably water sol. + citrate sol.)	2.1- 24.4	7.4
N	0.05- 2.24	0.50
K ₂ O water sol.	0.12- 3.50	0.80

Thirteen similar analyses made on a previous occasion gave:

	RANGES	MEANS
P ₂ O ₅ total	8.39-26.47%	18.50%
P ₂ O ₅ assimilable	2.26-15.10	8.92
N	0.04- 3.49	0.45
K ₂ O water soluble	0.45- 3.45	1.33

The total reserve of the cave was estimated as 45,000 tons or about 3800 tons of phosphorus.

LA BUSCA VIDA, 8 KILOMETERS SOUTH OF
BAHIA HONDA, PINAR DEL RIO

A complex of caves of which the largest was examined. Fresh guano occurs, and under it in one place a clay yielded 0.86% N and 0.51% total phosphate. Of the nitrogen 0.41% appears to have been free ammonia associated with the clay and 0.45% was present as ammonium salts. A relatively pure calcium phosphate containing 34.63% total P₂O₅, 24.00% assimilable P₂O₅, 0.20% N, and 1.00% water-soluble K₂O formed a definite stratum in the hall on the left of the entrance, and similar material was present

as irregular layers and concretions. Apart from the clay seven samples were analyzed, the ranges and means being:

	RANGES	MEANS
P ₂ O ₅ total	7.15-34.63%	14.07%
P ₂ O ₅ assimilable	3.50-24.00	8.50
N total	0.20- 1.60	1.40
K ₂ O water soluble	0.55- 1.25	0.85

The original reserve was about 4000 tons of phosphatic cave deposit, or about 245 tons of phosphorus.

CAMPANA, 7 KILOMETERS NORTH OF
CATALINA DE GÜINES, HABANA

A cave of simple form which had been previously exploited to a limited degree and contained deposits at least 2.4 meters thick. Seven analyses gave:

	RANGES	MEANS
P ₂ O ₅ total	16.50-31.52%	21.88%
P ₂ O ₅ assimilable	3.83- 9.93	5.83
N total	0.23- 0.66	0.35
K ₂ O water sol.	0.25- 1.10	0.36

The original reserve was about 6000 tons of phosphatic earth, or about 570 tons of phosphorus.

EL INFIERNO, ABOUT 4 KILOMETERS
NORTH OF TAPASTE, HABANA

A simple cave about 120 meters deep. The depth of deposit is not clearly indicated, though at least 37 cm. Four analyses are given:

	RANGES	MEANS
P ₂ O ₅ total	10.50-21.00%	15.80%
P ₂ O ₅ assimilable	6.35-13.30	8.60
N total	0.23- 1.77	1.07
K ₂ O water sol.	0.68- 3.94	1.57

The original reserve was about 2500 tons, or about 170 tons of phosphorus.

ISLE OF PINES

Agéton examined 11 caves. The ordinary phosphatic cave earth dried at 100° C., as were all his samples, had the following proximate composition:

		MEANS, ALL CAVES
P ₂ O ₅ total	1.91-39.41%	16.95%
P ₂ O ₅ assimilable	0.00-13.76	5.80
N total	0.00- 4.33	0.92
K ₂ O water sol.	0.00- 2.05	0.74

Some localities contained supposed bird droppings as well as bat excrement. One sample of the avian material from a rock crevice is said to have contained 4.33% nitrogen and 6.90% P_2O_5 . In one cave, known as Senado, property of Sra. Eusebia Gonzales de Averhoff, a pale material on the surface of the deposit contained:

P_2O_5 total	41.50%
P_2O_5 assimilable	34.89
N	1.00
K_2O water sol.	0.30

It is reasonable to suppose that this material contained either brushite or monetite.

The largest deposit was in the cave Senado where the original reserve apparently corresponded to about 1150 tons of phosphorus. All the other localities contained very much less phosphate, in no cases corresponding to as much as 100 tons of elementary phosphorus.

MOLINE DE ZARAGOZA, BODEGA DE
ZARAGOZA, HABANA

Ten samples were analyzed giving:

	RANGES	MEANS
P_2O_5 total	7.00–21.80%	11.60%
P_2O_5 assimilable	1.00– 8.20	3.80
N	0.36– 2.00	0.72
K_2O water sol.	0.33– 1.35	0.72

The deposit appears to have been about 1.2 meters thick and to have composed a reserve of about 1000 tons corresponding to about 56 tons of phosphorus.

CAVE NEAR MATANZA

The only data are nine analyses giving:

	RANGES	MEANS
P_2O_5 total	3.57–31.25%	12.86%
P_2O_5 available	2.13–13.02	5.81
N	0.35– 2.15	0.83
K_2O water sol.	0.42– 3.08	1.41

JAMAICA

Cave guano undoubtedly occurs in many caves in Jamaica, but little has been written on the occurrences.

Osburn (1865) records *Artibeus j. jamaicensis* living in great numbers in Mahogany Hall Cave, the floor of which had become covered with a deposit of dung, in which etiolated seedlings of the bread-nut tree (*Brosimum*) were rooted. This observation indicates that as elsewhere in the West Indies frugivorous as well as insectivorous bats contribute to the deposits.

The following analysis is given by Voelcker (1878a):

Moisture	23.07%
Organic and volatile	23.65
N	1.26
CaO	20.40
$(Al,Fe)_2O_3$	5.64
Alk. salts	2.22
P_2O_5	16.03
SO_3	2.22

Cousins (1903) gives 35 analyses. The data in table 37 indicate the composition of material from the only two localities that are mentioned by name, as well as the means and extremes for the substances determined.

All the analyses giving both nitrogen and phosphate contents are incorporated into figure 81, which gives a distribution comparable to that derived from the bat guanos of other West Indian islands. Mr. C. Bernard Lewis informs me that a number of Jamaican caves containing deposits do not appear to have recently been inhabited by bats.

BAHAMAS

The cave guano deposits of the Bahamas raise certain difficulties. An anonymous re-

TABLE 37

	H_2O	Organic	N	P_2O_5	K_2O
St. Thomas	35.8%	47.6%	7.6%	5.1%	1.4%
St. Catherine					
(surface layer)	35.0	53.3	8.8	2.2	0.5
St. Catherine	24.5	39.1	5.6	2.3	0.5
St. Catherine	35.4	18.0	1.1	2.3	0.4
St. Catherine	36.1	23.3	1.3	4.0	0.6
Extremes	8.6–61.9	12.8–72.3	0.2–10.5	0.5–13.8	0.3–4.7
Means	30.9	33.4	4.5	5.3	1.3

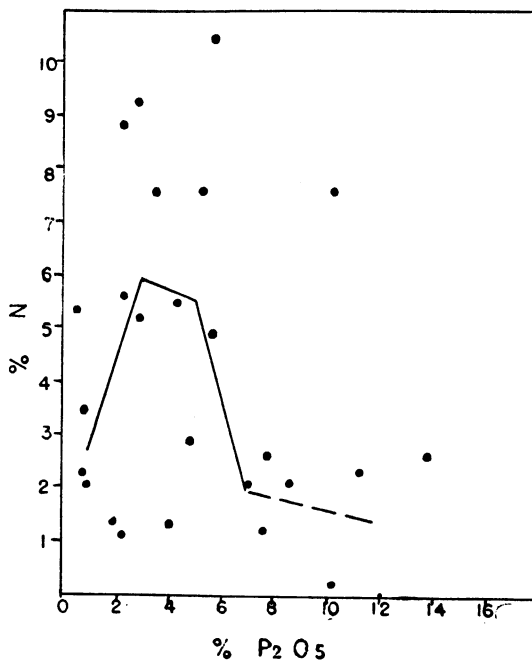


FIG. 81. Relation of total nitrogen to phosphate in Jamaican cave guanos.

port (Anon., 1876) indicated an estimated 400,000 tons of guano on the Bahama Islands. Although the Bahama Bank is not a particularly productive part of the ocean, it might seem reasonable to suppose that at least part of this material was deposited by bird colonies, as on other West Indian localities. The only two detailed accounts, however, indicate that Bahaman guano was obtained from caves, and in the first of these accounts it is specifically called bat guano.

Voelcker (1878a) indicates that Bahaman guano imported into England came from caves, frequented by numerous bats on Guanahani (San Salvador or Watling Island) and other islands in the group. It was dark brown in color, with little odor of ammonia, and contained fragments of coral and limestone.

It was often too damp or lumpy to apply directly to the land without being dried and sifted.

Voelcker gives three relatively complete analyses:

H ₂ O (moisture)	9.45%	21.27%	11.39%
Organic matter	11.41	27.97	16.45
Total N	1.49	1.32	2.73
N·NO ₃	0.55	0.23	0.09
Total P ₂ O ₅	14.32	4.59	8.64
Water-sol. P ₂ O ₅	1.27	0.25	0.76
CaO	20.13	17.53	12.32
MgO	0.13	1.12	3.83
CO ₂	—	8.53	1.04
SO ₃	11.08	0.66	14.27
Fe ₂ O ₃	7.29	5.57	4.33
Al ₂ O ₃	5.14		
KCl	1.46	2.61	10.16
NaCl			8.62
Indet.			—
Insol. silica	17.44	9.84	8.60

A number of less complete analyses are also given (see table 38).

The second account of Bahaman guano deposits relates to an island designated Breezy Point or Cape Comet 20 miles west of Grand Turk at the eastern end of the archipelago. The island bears a range of hills which apparently just fall short of an altitude of 50 meters at their highest point, but in the region of the guano caves on the western side of the island are not more than one-third of this height. Sharples (1884), who describes the locality, says that raised bench marks occur on the island, that the caves are wave cut, and that similar caves are being formed today wherever the sea washes a limestone bluff. In most cases the roofs of the caves are very thin and in places have collapsed to form entrances. Some of these entrances apparently were formed by roots breaking through the thin limestone roof. The only cave of which any dimensions are

TABLE 38

H ₂ O (moisture)	27.05%	23.46%	27.73%	20.61%	31.12%	31.49%
Organic matter	14.72	11.38	21.18	11.10	10.74	11.18
Total N	1.01	0.80	2.99	0.86	1.08	1.37
N·NO ₃	0.33	0.27	1.06	0.32	0.24	0.77
P ₂ O ₅	13.77	12.34	21.09	12.61	15.20	13.99
CaO	25.75	30.90	16.04	32.78	26.70	25.96
Insol. silica	4.79	3.04	2.99	1.64	1.14	1.04

given seems to be over 100 meters long. The interiors of the caves were deficient in stalactites and stalagmites. Water showing tidal ebb and flow filled the depressions and channels of the cave floor where this lay below sea level.

A red cave earth covered the dry parts of the floor of these caverns. In places it virtually filled the entire height of the cave with a deposit 7 to 8 meters thick. This cave earth is described as a mixture of sulphate and phosphate of lime with a small amount of alkali chloride and a variable amount of organic matter. It contained very little calcium carbonate. The water content of the undried material ranged up to 40%. The following analysis is given of a partially air-dried sample:

H ₂ O (moisture)	30.60%
Organic matter	9.98
Ca ₃ P ₂ O ₈	33.35
CaSO ₄	21.80
K ₂ O	0.32
Na ₂ O	0.14
SiO ₂	1.00

Chlorine, CO₂, Al₂O₃, and Fe₂O₃ are said to have been present. It seems unlikely that phosphate and sulphate would represent exactly the entire calcium content, so that the analysis is best left in its original form. There was apparently some of the deposit lying below sea water, and this is said to have contained little gypsum and when dried consisted of nearly 70% calcium triphosphate. Sharples supposes from this that the calcium sulphate of the main deposits could not have been derived from sea water, but he gives no alternative explanation of its presence. It is, however, possible to suppose that the sulphate is derived from sea spray percolating through the caves, which at a subsequent time

may have received enough fresh water from rain to remove most of the chloride. This explanation may be unnecessary, as some of the inland caves of Puerto Rico contain bat guano in which there is a very considerable quantity of calcium sulphate.

Sharples indicates that very few organic remains were present in the deposit, but that a sample of guano from a neighboring cay contained many fish bones. It is not entirely clear that this sample came from a cave.

The quantity of guano present was evidently very great. Sharples indicates that one mass in a cave was believed to consist of 1000 tons of guano and that 300,000 tons were present in the whole group of caves.

The origin of the deposits is by no means clear. Voelcker speaks of numerous bats on Guanahani Island, but Sharples found only a few in the caves that he examined. If he is correct in his belief that the food of whatever organism produced the deposit was mainly fish, it is evident that either the fish-eating bat *Noctilio* or some cave-breeding bird must have been responsible. The modern species of *Noctilio* is not apparently a markedly social animal, though it is known to produce small deposits of guano near San Juan, Puerto Rico, and apparently also on Mona. No social cave-breeding birds are known to form large colonies in the region at the present time, though the occurrence suggests Anthony's observations of the filling of caves on San Benito Island off Lower California with the guano of *Puffinus opisthomelas*. It is not impossible that these Bahaman deposits were made by some extinct species, and C. Bernard Lewis' remarks about the guano caves of Jamaica may indicate that formerly more deposits were produced in caves throughout the entire Caribbean region than there are today.

CAVE GUANO IN NORTH AMERICA (UNITED STATES AND MEXICO)

Very considerable quantities of bat guano have been discovered in caves in the southern United States and in Mexico. In general it appears that the largest of these deposits occur in limestone caverns within the range of the Mexican free-tailed bat, *Tadarida mexicana* (Saussure). This highly social species is distributed through Mexico from the state of

Pueblo, northward on the west coast of America into southern Oregon. It has been recorded as far north as Kansas in the central part of its range, but in the east it is apparently more limited in its latitudinal extension. In Texas its eastward limit coincides with the eastward extension of mesquite (*Prosopis glandulosa*) as an important ele-

ment in the flora and in general the species may be regarded as characterizing the arid Lower Sonoran Zone. It is not confined to caverns, but on occasions may be found in immense numbers in old buildings, from which guano may be collected. In an exuberant but uncritical and somewhat uninformative work, the cover of which is decorated with a bat-winged angel holding a bat mask and dancing over a swamp, Campbell (1925) has described the building of a successful artificial roost for this species near San Antonio, Texas. Other attempts to cultivate these bats appear to have been unsuccessful (Nelson, 1926). Campbell, whose work is full of testimonials and divagations of one sort and another, claims that his successful bat roost was constructed after a careful comparison of caverns containing colonies with adjacent caverns lacking colonies. Unfortunately the particular features that characterized the structure of the inhabited caves and that were incorporated into the architecture of the successful roost appear nowhere to be described. Campbell's main contention was that *Tadarida mexicana* feeds almost exclusively on malarial mosquitoes. The evidence that he gave is totally inadequate, and it appears from the observations of other investigators (Nelson, 1926; Bailey, 1931) that the food of this bat consists mainly of moths and beetles. Nevertheless Campbell's book is of some interest in providing incidental details of the occurrence and working of Texas bat guano.

In Florida and in the coastal regions of South Carolina, Georgia, Alabama, Mississippi, and Louisiana, the allied *Tadarida cynocephala* (LeConte) occurs. This species, though it may form great aggregations in deserted buildings, is apparently not certainly known to produce guano in natural cavities. In western Texas and northeast of the range of *Tadarida mexicana* bat guano has been found in a certain number of caverns in commercial quantities. Moreover, many caves in Georgia (Hess, 1900), Alabama, Arkansas, West Virginia, Kentucky, Tennessee, Missouri, Indiana, and Illinois (Gale, 1912) contained cave earth rich enough in nitrate to have been exploited in saltpeter manufacture when external sources were unavailable, notably during the War of 1812 and the Civil War. It is probable that

in a number of cases the nitrate of cave earth is derived from nitrification of ammonia derived from bat excreta (Nichols, 1901; Gale, 1912). Many other sources of the nitrate, such as human occupation, the excreta of terrestrial mammals, and nitrification in organic soils (Hess, 1900) overlying porous, cave-bearing limestones, however, certainly exist.

Apart from the wetness of the caves northeast of the range of *Tadarida mexicana*, guano production is limited in this area by the fact that most cave-frequenting species of North American bats use the caves mainly as hibernacula. Since such bats in general do not feed during the winter they do not produce guano. *Myotis grisescens* Howell appears to provide a notable exception. This species inhabits caves from Alabama northward into southern Indiana. It appears to be present in its main haunts mainly in the summer. In Saltpetre Cave, Rogersville, Alabama, in Rocheport Cave, and to a less extent in Hunter Cave, Missouri, and in Nickajack Cave, Tennessee, the best-known habitats of the species, its populations are largely replaced by *M. sodalis* Miller and Allen in winter (Mohr, 1932, 1933; Guthrie, 1933). *M. sodalis* is itself a highly colonial species in winter, aggregating in caverns in enormous numbers throughout its range from Tennessee and northern Alabama northeastward to Maine. The summer habits of this bat do not appear to be adequately investigated, but according to Guthrie it is intermittently active in Missouri throughout the winter, differing in this respect from *M. l. lucifugus* which is a strict hibernator. While this behavior may not hold over the entire range of *M. sodalis*, it appears to explain the fact that in some caves, notably those of Indiana in which the species occurs in enormous numbers in winter but from which *M. grisescens* is absent, a certain amount of guano has been deposited.

At least one record is available of a species of *Corynorhinus* producing guano in a cave in Oregon, but it seems likely that the cave-frequenting members of this genus are usually not sufficiently social to form a significant deposit.

The specific records of cave guano, or of substances derived from it, in Mexico and the United States are considered below.

MEXICO

According to Dovalina (1928) bat caves occur in the following localities in northern Mexico:

State of Coahuila: Muzqiz, annual yield of at least 300 metric tons

State of Chihuahua: Caves in district of Brava, capable of yielding at least 200 metric tons.

Caves in the districts of Camargo and Jimenez
State of Durango: Caves in the territory of Partido de Inde. These and the preceding are said to be capable of yielding a minimum of 1000 metric tons

State of Nuevo Leon: Caves 10 kilometers from Villa Garcia, at an altitude of 973 meters, northwest of Monterrey, in Cretaceous limestone

State of Vera Cruz: Caves in the territories of San Antonio (Paso del Toro), in the municipality of Naolinco, capable of yielding at least 50 metric tons per annum

Presumably the conditions in all these caves are comparable to those of the Texan and New Mexican localities. The estimates of the reserves given by Dovalina are probably quite unreliable (p. 126).

Brand (1937) states that in the limestone caverns and rhyolitic tuff caves of Chihuahua great numbers of *Tadarida mexicana* and *Antrozous pallidus* have deposited enormous quantities of guano. It is probable that the first-named species is the most important here as in New Mexico and Texas.

Farther south there are records of guano deposits, in caves in lava flows, which deposits have been formed by other species of bats. Ward (1904) records in a long, tunnel-like cave of such a nature known as El Infernillo near Jalapa, Vera Cruz, a layer of dry spongy guano "at least two feet deep . . . and some places where it had warped away from the walls, showed it to be not less than eighteen inches thick." The bats responsible for this deposit were *Mormoops megalophylla* Peters, *Chilonycteris rubiginosa mexicana* (Miller), *Natalus mexicanus* Miller (sub *N. stramineus* Gray), and *Pteronotus davyi fulvus* (Thomas) (sub *Dermonotus davyi* Gray). The four species apparently remained in separate aggregations in the cave, but no details are given. The total population is estimated at thousands if not millions. The bats evidently emerged nightly from the small opening of the cavern.

Ward describes a very large colony of

Myotis velifer (Allen) in a cave in lava at Las Vegas, Vera Cruz, but gives no indication of guano formation and also mentions the fact that in a shallow cave near Zacoalpan Amilpas, District of Jonacatapec, Morelos, he found the guano of *Desmodus rotundus murinus* (Wagner) to be a thickish black fluid. Mr. Benjamin J. Dontzin has confirmed the nature of the guano of this blood-sucking vampire bat, which he observed in caves near Pujal, San Luis Potosi. Ward's records do not indicate *Tadarida mexicana* as an important cave bat in the state of Morelos.

TEXAS

Phillips (1901) states that significant accumulations of bat guano occur in caves along a line stretching southwest from Lampasas County through Burnet, Llano, Mason, Williamson, Blanco, Gillespie, Hays, Comal, Kerr, Medina, Uvalde, and Edwards counties. Limestone caves in San Saba, Travis, and Bandera counties had not yielded deposits of any commercial importance. The limestone

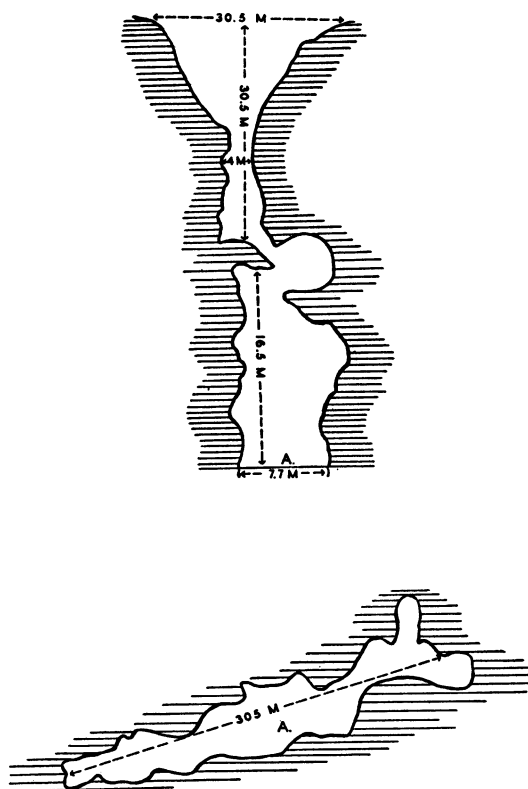


FIG. 82. A Texan bat cave. After Phillips.

of the belt containing bat caves belongs in general to the Comanche series of the Lower Cretaceous (Sellards, Adkins, and Plummer, 1932).

The first observations of the guano of these caverns is said to have been made at least as early as 1856, when it was noted that the brown deposits in certain caves were combustible. Some time prior to 1871-1873 a hunter is said to have attempted to smoke a bear out of a cave in Blanco County and in doing so to have generated a great explosion, after which the cave deposit continued to burn for two years.

As in Missouri, saltpeter was made from the bat guano of caves during the Civil War. Campbell indicates that in the extraction of saltpeter from bat guano obtained in caves near San Antonio, layers of guano were put in hoppers, alternating with layers of wood ashes, the layers being separated by brown weed. Water was then poured through and conducted to large, open, cast-iron boilers for concentration.

The bat caves of Texas still yield small amounts of fertilizer on an annual income basis. Nelson (1926) indicates that from the Cibolo Creek Cave north of San Antonio 60 to 70 tons of guano are recovered annually. Another cave on the Eno River near Uvalde is said to have had a comparable annual yield. The caves are therefore of some value as property and a Texas Bat-Cave-Owners' Association was established by Campbell (1925) about 1917, with 18 to 20 members, who seem soon to have lost interest in this curious organization.

An analysis from an unspecified cave is given by Phillips:

P ₂ O ₅	0.59%
SO ₃	1.43
N total	10.48
Non-nitrogenous org.	50.00
Ash	12.47

This material seems to have lost phosphate rather than nitrogen diagenetically. One cave worked by a Mr. Badu of Llano yielded 1000 tons of guano.

Nelson (1926) describes Cibolo Creek Cave north of San Antonio as "a great tunnel sloping gently downward for 200 or 300 yards through the limestone formation toward the creek valley below, and widening out at the lower part on a great room some 75 feet high and 150 feet wide." The bats hung in great numbers, possibly millions, from the roof of this large chamber, and, although the guano had been collected during the previous winter, a layer an inch thick had accumulated by March 5, 1924. This seems to imply the deposition of at least a tenth of a meter per annum. The major factor limiting the thickness of guano in old virgin caves seems to be the liability of nitrified guano to explosive combustion. Campbell says all the bat caves of Texas show evidence of fires which he supposes may have started spontaneously and which may last for months. In extreme cases up to 15 feet of compacted ash has been discovered.

A few chemical studies of supposedly Texan bat guano have been published without details of occurrence (Harf, 1904). A number of specimens submitted from El Paso, Texas, contained up to 14.66% H₂O, from 1.54% to 9.37% N, 0.58% to 6.61% K₂O, and 2.81% to 24.26% P₂O₅. Examples submitted from San Marcos contained from 0.28% to 9.55% N, 0.24% to 1.89% K₂O, and 1.50% to 23.12% P₂O₅. Without more details of occurrence these determinations are of little interest, but can be used in the diagram indicating the relationship of P₂O₅ to N in Texan and New Mexican bat guanos (fig. 84). Two incomplete analyses of Texan guano (I, II) and two of guano ash (III, IV), presumably from cave deposits that had caught fire, are given by Adriance, Tilson, and Harrington (1895).

	I	II	III	IV
H ₂ O (moisture)	12.63%	13.41%	—	14.91%
P ₂ O ₅ total	3.68	4.84	23.85%	16.70
P ₂ O ₅ sol.	—	0.30	—	0.46
P ₂ O ₅ citrate sol.	—	3.15	—	11.23
CaO	—	—	33.50	22.73
MgO	—	—	—	2.69
K ₂ O	2.03	—	0.90	0.64
N	11.91	10.04	—	—

Data given by Harrington (1899) and Frapps (1906) refer solely to nitrogen (1.66%–11.44% N) and available (i.e., citrate+water-soluble) phosphorus (0.92%–7.70% P_2O_5) and are of little or no interest in absence of further details.

Certain occurrences of niter in Texas are of some interest. At a locality called Agua Fria, about 58 miles south of Alpine, niter has been found encrusting the overhung base of a bluff of rhyolite. In view of the presence of organic matter derived from an ancient Indian camp it is by no means certain that this nitrate is derived from bat guano. Another locality at the base of a limestone bluff lies about 50 miles south of Alpine. Here small caves are said to contain unspecified animal excreta. A third locality for niter, about 70 miles southeast of Alpine, apparently lies below another camp site. Three small caves in Brewster County are also mentioned by Mansfield and Boardman as having contained a small quantity of bat guano.

Small deposits of cave niter, which may have been derived from bat guano, have been found in Lubbock County on sandstone, in Presidio County on rhyolite and fractured cavernous basalt, in Reeves County on a porphyritic rock, in San Saba County on limestone, and in Val Verde County on limestone (Mansfield and Boardman, 1932).

NEW MEXICO

The most important localities are the Carlsbad Caverns and certain other caves in the foothills of the Guadalupe Mountains in the Pecos River Valley. Twelve species of bats are recorded by Bailey (1928) in or near the cave, but only *Tadarida m. mexicana* is abundant enough to have produced significant guano. The main bat colony appears to occupy a part of the cavern near the principal natural entrance, and from the floor of this part of the cave very large amounts of guano have been removed. This lay over a stretch of cave floor 100 or more feet wide and a quarter of a mile long. Bailey estimates the total mass removed while the cave was exploited as at least 100,000 tons, but it is evident that this estimate is very conservative. The maximum thickness is said to have been 100 feet.

It was supposed by Bailey that the bats hibernated in the cave, but Christensen

(1947) finds that this is not correct. The maximum population is apparently present in late summer and early fall. From mid-October an irregular decrease in numbers occurs, and by the end of February usually no bats are present in the cave. Christensen believes that there is no period during which the bats are inactive; so long as they are present they attempt to feed, and lack of food rather than temperature is believed by him to determine the winter emigration. Bailey found that at 10° C. the bats were torpid in captivity, while at 15.6° C. they were active. The air at the bottom of the bat cave lay at 12.8° C. and was said to vary little throughout the year. *T. m. mexicana*, as do other guano bats, emerges from the cave in immense columns in the evening. Allison (1937) states that the column is visible for 10 miles and that observation of the bats led to the discovery of the cave. He suggests that the bats are very sensitive to changes in the circulation of the air in the cave and that the signal for emergence at night is a change in air temperature at the mouth of the cave as the sun sets, causing a change in the air movements in the vicinity of the cave.

Allison estimated that on June 16, 1936, the population consisted of about 8,700,000 individuals. It is possible that there are even more bats normally present in the late summer, and probably fewer in the spring and early summer when Bailey estimated at least 3,000,000 to be present in the cave.

Bailey states that after the old guano had been removed from the cave, a layer about 3 inches thick had formed in four years. This implies a rate of deposition of about 1.9 cm. per year. Bailey found experimentally that during the end of April guano was falling from the colony at the rate of about 1 mm. in 44 hours. He supposed that it would accumulate more rapidly when feeding conditions were better later in the year. Since his figure implies a deposit of about 10.9 cm. in 200 days, it is quite excessive relative to the actual deposition observed by him since exploitation was abandoned. The discrepancy is doubtless due to variation in the density of the colony hanging from different parts of the cave roof. The lower estimate of 1.9 cm. per year would, however, imply that a layer about 100 feet, or 30 meters, thick could be deposited in less than 2000 years.

No analyses certainly referable to material from Carlsbad Cavern appear to be available, but Bailey says that the lower layers were less rich in nitrate than the upper layers. The following analyses of material submitted by residents of Carlsbad to the New Mexico Agricultural Experiment Station, presumably at least in part refer to material from the cave:

H ₂ O	N	P ₂ O ₅
—	1.40%	2.91% (trace K ₂ O)
23.88%	8.68	3.70
16.51	5.74	4.48
17.08	4.97	12.02
—	4.27	—
—	9.03	—
14.55	5.67	11.34 (0.48 K ₂ O)
—	5.04	8.06 (0.66 K ₂ O)
—	0.48	11.20 (0.48 K ₂ O)

The only New Mexican guano cave other than the Carlsbad Cavern that has been described in detail is the remarkable pit on the eastern rim of a small crater known as Aden Crater, about 39 kilometers southwest of Las Cruces. This pit, in the basaltic lava of

the extinct volcano, represents an old fumarole. The contour of the pit is very irregular (fig. 83). The lower part is filled with a deposit of bat guano (Longwell *in* Lull, 1929). The most remarkable feature of this locality was the presence on the surface of the guano layer, not entirely covered by the deposit, of an intact skeleton of a ground sloth, *Nothotherium shastense* Sinclair. The skeleton, to which some skin with hair still was attached, is beautifully described and illustrated by Lull (1929). *N. shastense* is otherwise known associated with middle Pleistocene mammals in the Rancho la Brea asphalt in California. Lull found it difficult to believe that his skeleton was as old, in view of the preservation of some of the soft parts. The occurrence of an extinct and otherwise Pleistocene mammal at the surface of the guano indicates that some of the New Mexican deposits are of very considerable antiquity.

In addition to the analyses of material from Carlsbad given above, Harf has published numerous determinations of material submitted by individuals from various localities in New Mexico: Cuchillo, Deming, Faywood, Las Cruces, Lava, Malaga, Mesilla Park, Roswell, San Marcial, Santa Fe, and Senovio Avalos (*sic*). These analyses, except those indicating more than 3% K₂O, are incorporated in the diagram (fig. 84) indicating the relationship of nitrogen to phosphate in Texan and New Mexican bat guanos. It is by no means certain that all the specimens actually came from the localities from which they were submitted. Much material forwarded from Las Cruces by J. R. De Mier, who worked a series of caves at Lava, presumably came from the latter locality. The most important source, other than Lava and Las Cruces, was the Patterson Guano Company, at Malaga.

Some of the specimens, particularly some among the series submitted from Las Cruces, and one from San Marcial, were extraordinarily rich in potash, the two richest containing:

	K ₂ O	N	P ₂ O ₅
San Marcial	20.96%	1.23%	31.76%
Las Cruces	21.38	2.63	25.46

It is almost certain that these analyses refer

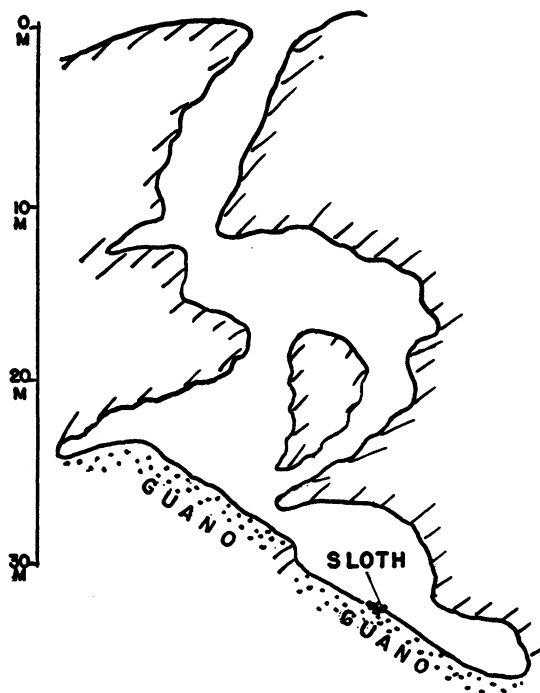


FIG. 83. Ground sloth cave at Aden Crater, New Mexico. After Longwell.

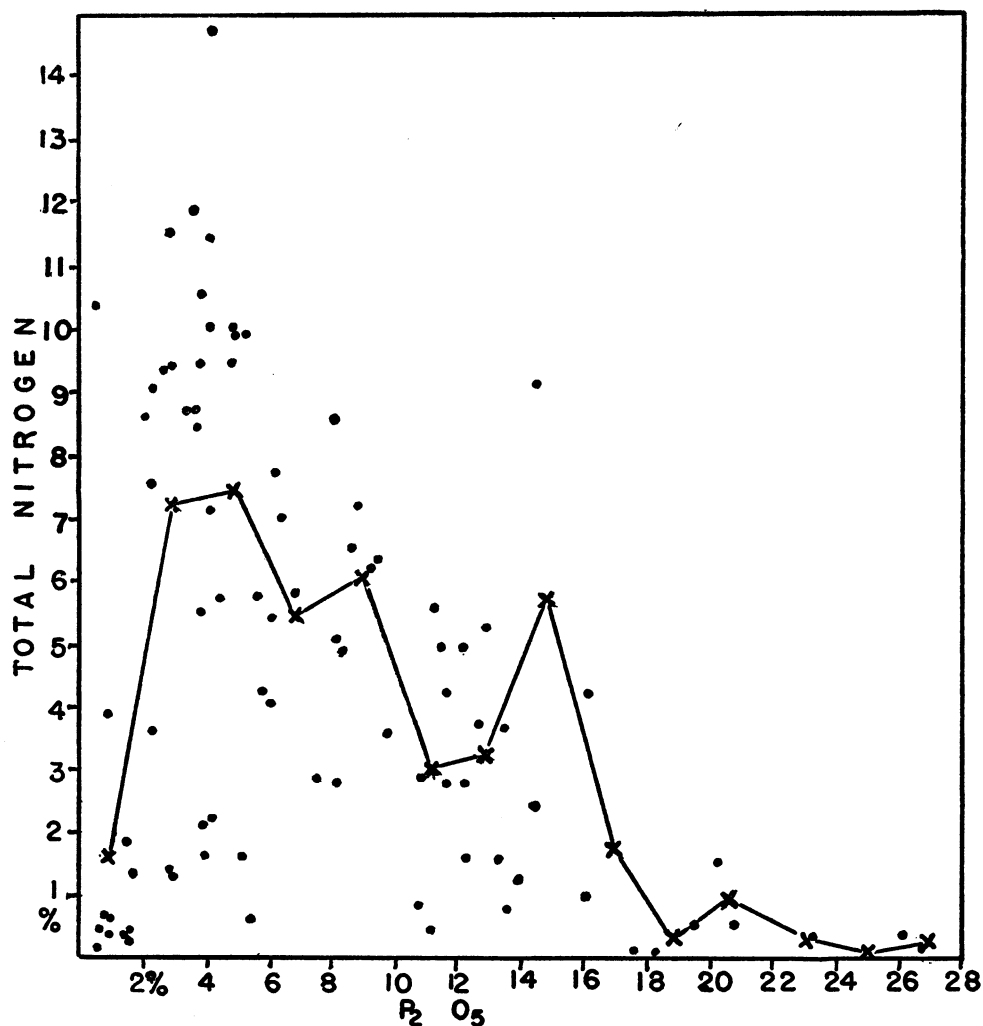


FIG. 84. Relationship of total nitrogen to phosphate in Texan and New Mexican guanos.

to the ash of burnt guano which had been greatly enriched in niter before combustion. Two other samples containing 19.72% and 20.74% K_2O submitted from Las Cruces are expressly described as guano ash. Niter is known from the guano locality at Lava, which may actually have yielded the specimens sent from Las Cruces. Niter is also known from Dark Canyon 9.6 kilometers east of Queen Post Office, Eddy County, also from near Rodeo, and in the Animas Valley, Hidalgo County. Nitratite has occurred on the face of a cliff of tuff south and east of Las Cruces. There is therefore nothing improbable in the assumption that samples

with high potassium contents actually contained KNO_3 , or K_2CO_3 derived from the combustion of organic matter and niter. The amount of niter that occurred in the guano caves at Lava, New Mexico, was very considerable. The locality is described by J. R. De Mier (Mansfield and Bordman, 1932) as a series of tunnel caves that originated from an old crater, "10 miles east of Lava station on the Santa Fe Railway," and which extended "for about a mile and a half south." They are covered with up to 10 meters of lava overflow which in places has collapsed, giving access to the caves. Eight hundred tons of guano, 3333 tons of phosphate of

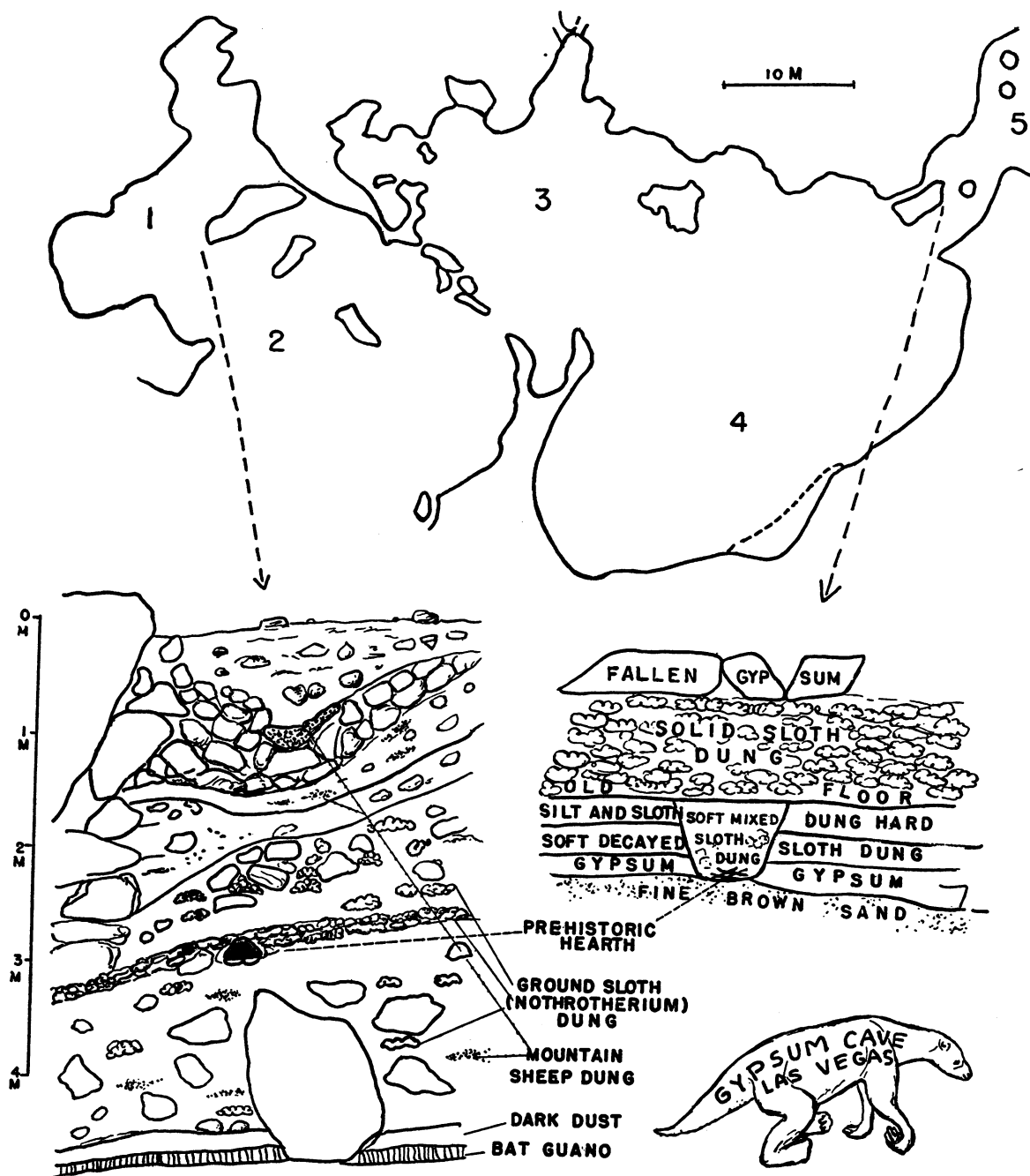


FIG. 85. Section in Gypsum Cave, Nevada. After Harrington.

lime and, from one place, 125 tons of potassium nitrate were mined here between 1899 and 1902. The nitrate was so pure that it melted in the rocks and looked like thick syrup. If the high potash guano samples came from this or similar localities it is reasonable to suppose that the potassium was derived from the volcanic material.

MISCELLANEOUS WESTERN OCCURRENCES

ARIZONA: Guild (1910) states that nitrocalcite has been found in fissures in Carboniferous limestone in the railroad cut facing the Gila River about 2 miles above Winhelman. Cameron (1912) indicates nitrate at Briggs, Yavapai County, without details of the occurrence. Laudermilk and Muntz (1938) record *Nothrotherium* dung forming deposits in Rampart and Muav caves in the lower Grand Canyon.

CALIFORNIA: Bailey (1902) states that niter has occurred in the desert northeast of Salton, Riverside County, California. It is possible that three analyses of bat guano sent to Harf from Riverside, California, were from this locality. Harf found:

K ₂ O	N	P ₂ O ₅
17.34%	1.00%	30.20%
16.76	0.81	31.22
15.10	1.36	30.52

These analyses suggest that the samples consist largely of a guano that had been enriched with KNO₃ prior to combustion. The region of their occurrence is within the range of *Tadarida mexicana*. Nitratite is said by Bailey (1902) to have occurred as crystals lining a cave in Calico, California. Guano from the houses of pack rats, *Neotoma fuscipes streator* Merriam, is recorded from the chaparral country of California (Streator, 1920).

NEVADA: A deposit of almost pure niter has been found as fissure filling or as a seam in soil and rock debris at the base of an overhanging cliff of rhyolite in Grass Valley Creek, a tributary to Little Highrock Canyon, at the northern end of the Granite Range, Gerlock, Washoe County, Nevada (Gale, 1912). At an adjacent locality a supposed bat guano was discovered. Several other incrustations and seams appear not to contain appreciable nitrate.

	I	II	III
Inorg. insol.	34.10%	10.04%	14.58%
NO ₃	tr.	52.40	50.42
SO ₃	—	small	—
K	5.45	33.61	31.42
Na	0.67	1.07	1.28
Cl	3.18	tr.	tr.
	(non-volatile)		
CaO	—	small	small
P ₂ O ₅	0.64	—	—

- I. Bat guano from under a cave in upper part of Grass Valley Creek; ammonia present.
- II. Nitrate from seam at base of cliff in lower part of creek.
- III. Nitrate from fissure filling near locality of II.

It is stated by Gale that niter has occurred in canyons bordering the west side of Railroad Valley in the center of Nevada. Some of these occurrences may be within the range of *Tadarida mexicana*.

While Lull's ground sloth was evidently associated with bat guano, a very remarkable deposit of the dung of *Nothrotherium shastense* itself occurred in Gypsum Cave about 20 kilometers east of Las Vegas. It is a wide, irregular cave descending quite steeply for about 30 meters. The main outer part (room 2) had a height of about 3 to 6 meters. There are lower smaller chambers at the farther end of the cave which is about 90 meters long in all. The stratigraphy and archaeology of Gypsum Cave have been described by Harrington (1933) in one of the classical contributions to American prehistory.

The greater part of the cave filling consisted of the dung of *Nothrotherium* mixed with stones that had fallen from the roof. In parts of the cave much gypsum has formed and in some places constituted a hard floor over other deposits. As well as coprogenic deposits due to the ground sloth, similar evidence of occupation by mountain sheep was found in the outer part of the cave, at both high and low levels, and a basal layer of bat guano was also recorded at one point in the excavation of the outer chamber designated room 1 (fig. 85). Very clear evidence of human occupation below the *Nothrotherium* layers was obtained. No chemical data are available, but Laudermilk and Muntz (1938) found microscopically that 80% of the vegetable matter forming the sloth feces consisted of remains of *Yucca* which must have been

the habitual diet of the animal. Bones of extinct camels (*Tanupalama* and *Camelops* spp.) and horses were also discovered, and the archaeological findings were very rich.

UTAH: Gale (1912) records a material containing 19.18% K and 28.53% NO_3 mixed with 46.04% insoluble material from the talus at the foot of a cliff of rhyolitic lava in Greenwich Canyon (latitude $38^\circ 27' \text{ N.}$, longitude $112^\circ 01' \text{ W.}$). This was alleged to be correlated with the abundance of "bat nests," though it "is not certain that the nests are those of bats," a qualification that the biologist will doubtless find reasonable. Other occurrences are known in Hobbie Canyon, south of Provo, at Fillmore, Millard County, at Parawan, Iron County, and disseminated in limestone and lava above the Rob Roy mine in Wildcat Canyon.

IDAHO: Small quantities of nitrate, apparently in cave deposits, are known at Soda Springs and Pocatello, Banrock County; in Blaine County; in Wayne County; and near the Utah-Nevada line.

OREGON: Bailey (1936) reports that hundreds of *Corynorhinus rafinesquii townsendii* (Cooper) formerly inhabited a cave near Portland, Oregon. Unfortunately the guano produced was ignited by vandals, and the colony left the cave. The account suggests a fairly definite deposit.

Farther north, niter is recorded from cavities in calcareous tuff in British Columbia, but no indication that such material is derived from the excrement of bats is available (Hoffman, 1890).

ALABAMA

A cave "on the plantation of Mr. B. F. Watkins," Lauderdale County, on the Tennessee River about 64 kilometers west of Huntsville, was worked for niter during the Civil War. The cave was inhabited by countless bats. The earth of this cave was examined by M'Murtrie (1874) who described it as dark brown, very light, and apparently consisting largely of the scales of insects. Analysis gave:

Moisture	11.60%
Total organic	39.26
Soluble organic	10.57

Nitrogen total	3.75
$\text{N} \cdot \text{NH}_3$	tr.
$\text{N} \cdot \text{N}_2\text{O}_5$	0.03
P_2O_5 total	2.81
P_2O_5 water sol.	1.31
Fe_2O_3	1.43
Al_2O_3	3.21
CaO	4.11
MgO	3.11
Na_2O	0.31

This is not improbably the Saltpetre Cave near Rogersville from which 62 specimens of *Myotis grisescens* were obtained by Holt. The collector is quoted as indicating that thousands of bats lined the ceiling in a solid sheet, while their droppings covered the floor in places to a depth of several feet (Howell, 1921).

MISSOURI

Albrecht (1921) gives a brief account of bat guano from caves in Missouri. He provides no indication of the species of bats producing the guano, but two records of other workers appear to refer to two of Albrecht's localities, and there can be little doubt that the major contribution is made by *Myotis grisescens*. Miller and Allen record that species from Marble Cave, Stone County, probably identical with the Marvel Cave in the same county discussed by Albrecht. Guthrie (1933) found Rocheport Cave to be inhabited by *M. grisescens* in summer and *M. sodalis* and *M. l. lucifugus* in winter. Since *M. sodalis* is said not to be a true hibernator in the region, it may well add to the deposits.

Albrecht describes the fresh guano of the Missouri caves as black when damp and brown when dry. The older material is reddish, pale brown, or gray when dry. Fresh samples from two caves at Rocheport, Boone County, and Zebra, Camden County, contained 10.44% and 10.35% N, respectively. The first of these samples apparently contained 1.97% $\text{N} \cdot \text{NH}_3$. Some of this ammonia may have been formed by hydrolysis during the process of analysis, but it is certain that a considerable amount of ammonia nitrogen may be expected in such fresh samples. This ammonia is doubtless of urinary origin and is derived from the action of bacteria on urea. Albrecht states, on the authority of A. W.

Mcfarland of Blavistown, Missouri, that saltpeter derived from bat guano was used in the state in the manufacture of gunpowder during the Civil War. Gale (1912) notes that saltpeter has been found in caves in magnesian limestone in Pulaski, Maries, Callaway, and Ozark counties. This probably refers to the same period of exploitation. Most of the samples examined by Albrecht appear to have been low in nitrate, though no quantitative data are given.

The Missouri deposits appear to retain several per cent of nitrogen in the top 30 cm. or so of the guano, as is indicated in the nitrogen determinations on the following profiles:

Ink Cave, Shannon County	N
0-15 cm. (6 in.)	7.36% (referred to air-dried material)
18-30 cm. (7-12 in.)	6.42
33-41 cm. (13-16 in.)	1.96
Colleda Cave, Camden County	
Surface, nearly fresh	7.52
61 cm.	2.32
Marvel Cave*	
Surface	8.69
61 cm.	5.90, 5.24
91 cm.	0.31

* There appears to be some inconsistency in the presentation of the Marvel Cave analyses; these figures are presumably correct.

Nitrogen determinations of bat guano ranging from 1.3% to 8.10% are given for eight other caves in Pulaski, Dent, Laclede, Miller, Crawford, Montgomery, and Oregon counties. Phosphate and potash were determined on certain samples.

	N	P ₂ O ₅	K ₂ O
Marvel Cave, Notch, Stone County	2.71%	5.56%	—
Marvel Cave, Notch, Stone County	3.66	6.63	—
Marvel Cave, Notch, Stone County	3.98	6.27	—
Marvel Cave, Notch, Stone County	3.91	—	0.36%
Hoecker Cave, Miller County	7.30	2.50	1.90
Leasburg Cave, Crawford County	2.06	7.91	—
Oregon Cave, Oregon County	8.10	2.06	0.58

The Hoecker Cave deposit is interesting, for, in spite of the high nitrogen content of the air-dried material, the freshly collected guano is said to have contained 63% water. Another very wet sample, from Colleda Cave, described simply as saturated with water, and without indication of its relationship to the profile given above, contained 1.77% N. The retention of nitrogen in very wet guano and the presence of several per cent of nitrogen below the surface layers are in striking contrast to the conditions in tropical caves.

INDIANA

Niter has been obtained from the cave earth of caverns in the Mississippian limestone of southern Indiana, notably Great Wyandotte Cave, Crawford County, first worked during the War of 1812, Saltpeter Cave, Crawford County, and Saltpeter Cave, Monroe County (Blatchley, 1897), and from caves in Harrison County (Gale, 1912). Great Wyandotte Cave and Saltpeter Cave are known to be hibernacula of *Myotis sodalis* (Miller and Allen, 1928; Mohr, 1933; cf. Blatchley, 1897, sub *Vespertilio subulatus* Say). Such deposits of bat guano as occur in the Indiana caves are probably largely due to this species.

According to Blatchley the part of Wyandotte Cave called the Senate Chamber had an abundant bat population in November, and a section through the cave earth made in the course of archaeological investigation of this part of the cavern is indicated as capped by half an inch of bat dung. In Saltpeter Cave, Crawford County, Blatchley found 401 bats hanging in an area of 0.16 m². These large and concentrated populations, being developed mainly in the winter, evidently produce little guano in comparison with that deposited by *Tadarida*. The Indiana caves are moreover mostly very wet, and such guano as is produced will be largely lost by leaching, though there can be no doubt that the bats, along with other animals including man occasionally visiting the caves, are in part responsible for the enrichment of the cave earth in nitrate.

An analysis of the bat guano of Wyandotte Cave is given by Cox (1879):

Loss at red heat	44.10%
Organic matter	4.90
NH ₃	4.25
SiO ₂	6.13
Al ₂ O ₃	14.30
Fe ₂ O ₃	1.20
CaO	7.95
MgO	1.11
SO ₃	5.21
CO ₂	3.77
P ₂ O ₅	1.21
Chlorides of alkalis, loss	5.87

This material appears to be very impure.

TENNESSEE

A large number of caves in the eastern Highland Rim and Cumberland Mountains were explored by Bailey (1918). Cave earth had been used in niter manufacture in many of these caves, as was indicated by the remains of troughs and hoppers often encountered in them. Ninety-one nitrate and potash determinations by Glenn from the cave earth of 90 of these caves are given by Bailey. In only eight samples did the K₂O exceed 0.5%, and in only one did it exceed 1% (Saltpeter Cave, a rock shelter 8 kilometers southeast of Celina, Clay County, 1.02%). In only 11 samples did the NO₃ exceed 0.5%, and in but seven did it exceed 1%, the highest quantity being 2.39% (Saltpeter Cave, Marion County). Bat guano is recorded specifically from Burial Cave and Haile Cave, Flynn's Lick, Jackson County, in both of which caves there are bat roosts. It is said that cave earth from Hubbard or Bat Cave southeast of Irving College in Warren County was used as fertilizer and that a bat roost is known in Lost Cove Cave, southeast of Sewanee, Franklin County. Thus only about 4% of the caves are noted as having any indication of bats or bat guano today. It is to be noted that the exploration was conducted in late summer (July 15 to September 15, 1917) when *Myotis grisescens* is the only cave bat likely to have been present. This species was originally described from Nickajack Cave, Marion County, and is doubtless responsible for such modern guano as is deposited in the caves of Tennessee.

It is, however, not unlikely that a considerable amount of the cave earth noted in the Tennessee caves actually contained appreci-

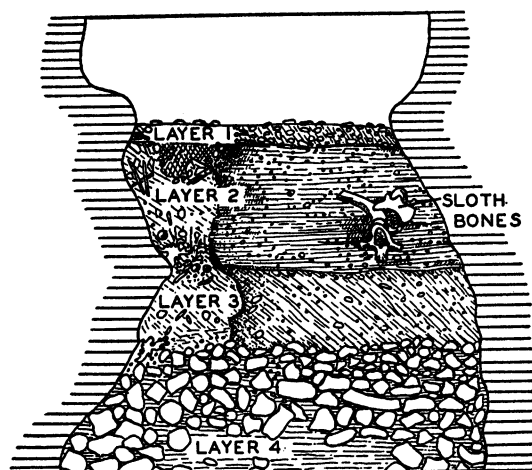


FIG. 86. Section in Big Bone Cave, Tennessee. Modified from Mercer.

able amounts of phosphate of chiropteran origin. One case in which the cave earth is known to contain much fecal matter and to be of some antiquity has been described.

BIG BONE CAVE: The stratification in part of the deposit has been described by Mercer (1897) who examined the cave in 1896. At that time most of the cave earth had been removed for the manufacture of niter. It was said that, during the War of 1812, 300 men were employed there in this occupation. About 270 meters from the entrance a relatively undisturbed section of cave earth was excavated. In the figure indicating the stratification the confused region on the left represents mixing of the layers by the burrowing of pack rats. The topmost layer 1 contained burnt sticks and probably largely represented disturbance by niter diggers. Below this, layer 2 consisted primarily of well-preserved feces of the pack rat, *Neotoma magister* Baird, with smaller amounts of porcupine dung. In this layer 12 bones of the giant sloth, *Megalonyx jeffersonii* Leidy, were obtained. These bones show remains of tendinous attachments. Tufts of hair, some rodent, some of uncertain origin, a large fecal mass of an unidentified herbivore, jaws of the bats *Eptesicus fuscus* and *Myotis keenii septentrionalis* (Trouessart) (sub *gryphus*), and numerous plant remains indicating a flora comparable to the present one were found associated with the sloth bones.

Below the stratum bearing the sloth bones

lay layer 3 which apparently formed the floor of the cave when the dead sloth came to rest there. It was more consolidated than layer 2, but Mercer suggests that its existence as a discrete layer may be local and due only to the decomposition of the large carcass lying on it. It contained a well-preserved specimen of the fly *Scenopinus fenestralis* (Linnaeus) which is supposed to be introduced in North America and can hardly be contemporary with the deposit in which it is believed to have been embedded. A bat jaw is referred to *Eptesicus fuscus*, but it is stated that the "bats here described" seemed larger than modern specimens. Porcupines are represented in layer 3.

Layer 4 is apparently the result of a wet clay drying and cracking, and the cracks then filling up with excreta from the layers above. It was not fossiliferous.

This occurrence is the only one in the southeastern states that gives any indication of the nature of the cave earth, and it seems clear from the account that the section described was not typical, even for the cave in which it occurred. It is evident that the de-

posit in general here was due to *Neotoma* rather than to bats, and that it was of post-glacial age but not very recent. It is most unfortunate that no other good sections in other caves in southeastern North America are now available.

OTHER OCCURRENCES IN EASTERN NORTH AMERICA

Gale (1912) lists, from a document prepared by the United States Geological Survey, the occurrence of cave nitrate in the following:

Arkansas, in caves in Marion and Newton counties¹

Illinois, in caves of Jackson County and on Cave Creek

Kentucky, in Mammoth Cave, and in small quantities in hundreds of other limestone caves in the southern and central parts of the state

West Virginia, in caves in Greenbrier, Monroe, and Pocahontas counties

All these occurrences were doubtless similar to those already described in the adjacent states.

CAVE GUANO ON PACIFIC ISLANDS

Several islands in the western Pacific are known to produce bat guano. Also records the deposits on:

	N	P ₂ O ₅	K ₂ O	INSOL., ETC.
Ponape	7.00%	5.10%	1.50%	—
Kusaie	8.16	1.00	1.00	10.00%
Palau	8.65	5.99	0.76	0.56
Palau	3.72	14.54	0.82	2.55

Also makes the statement that the bats producing the deposits are large and fly between trees by day feeding on insects and fresh mosses. Parts of this statement are obviously improbable.

MARIANA ISLANDS

Kanamori (1907) has described a brown, peaty-looking bat guano collected in caves on Rota and Saipan where it formed deposits several meters thick. Crusts and white particles occurred sparsely in the brown friable mass. These particles and crusts contained 8.45% P₂O₅ and gave qualitative evidence of

N and CO₂. The main mass of the material contained:

H ₂ O (hygroscopic)	14.2%
Organic matter	74.3
Ash	11.4

Two air-dried samples gave:

	I	II
Total N	14.89%	8.97%
N·NO ₃	0.06	—
N sol. in dilute acid (mainly NH ₃)	0.13	—
N in humus soluble in alkali	2.64	—
N liberated as NH ₃ by hot alkali	2.87	—
Total P ₂ O ₅	7.33	—
1% citric-acid-sol. P ₂ O ₅	1.50	1.75
K ₂ O	2.47	2.09

¹ Voelcker (1878a) gives analyses for Arkansas bat guano from two unspecified localities. One sample contained 6.64% P₂O₅, 0.46% N·NO₃, and 2.48% organic and ammoniacal nitrogen; the other, 3.76% P₂O₅, 2.18% N·NO₃, and 6.62% organic and ammoniacal nitrogen. Voelcker was struck by the high nitrate co-existing with organic nitrogen in the second sample and explains its presence by the light porous nature of the guano. He presents other analyses from uncertain localities, either in Arkansas or in Texas.

Though a large part of the organic matter may be chitin, it is obvious that a considerable part of the unidentified nitrogen must be present in some material such as a sclero-protein, containing more nitrogen than chitin does. Microscopic examination of the speci-

men indicated the presence of fragments of legs and wings and a few lepidopteran scales. The nitrogen proved practically unavailable in fertilizer experiments with barley in pot cultures.

CAVE GUANO IN AUSTRALIA AND NEW ZEALAND

VICTORIA

Cave guano, generally considered to be formed by bat colonies, has been reported from various parts of Victoria. MacIvor (1887) reports the following analyses of material from caves in the extreme southwest of the province:

	I	II	III	IV
Water	35.71%	19.97%	20.30%	37.48%
Organic matter	33.77	41.33	8.95	18.30
N total	1.08	1.28	0.91	1.89
Ash	30.52	38.70	70.75	44.22
P ₂ O ₅	2.41	11.88	7.45	9.98

I. Hamilton.
II. Portland.

III. Warrnambool, surface near entrance.
IV. Depth of 1.2 meters in center of deposit.

The Hamilton and Portland samples are regarded as fairly representative of the usual cave guano of Victoria. The deeper sample from Warrnambool is said to have had dispersed very sparingly through its mass minute crystals of newberyite.

Calcium phosphate is also recorded from a bone breccia in a cave at Buchan (Howitt, 1928).

The most important deposits of cave guano in the province were, however, at Skipton Caves, Mount Widderin, Skipton, in basalt, "on the estate of the Hon. Francis Ormond" near Skipton, southwest of Ballarat. The deposits were briefly described by Ulrich (1870) and MacIvor (1887, 1902a). There were apparently several caves, and in each a thick deposit of guano occurred. Ulrich says that this was perhaps 20 feet thick; MacIvor that it was 30 feet thick in some places. Ulrich indicates that the deposits were discovered by Messrs. Etheridge and Murray while making a geological survey shortly before 1870. At that time thousands of bats used the caves as daytime retreats and could be observed hanging in large clusters from the roof. MacIvor indicates that in 1887 the bats had deserted the caves.

MacIvor states that most of the guano was wet and dark brown or brown black in color, but that the older and drier deposits were light brown, powdery, and nearly odorless. In his later paper (1902a), however, he contrasts the upper or drier part with the moist depths of the guano. It is evident that the

drier and wetter materials of the later and earlier papers are the same, so that there is considerable doubt as to the stratigraphic relationship. The most remarkable feature of the Skipton guano was the occurrence of a considerable quantity of various crystalline minerals scattered throughout the deposit. Struvite was recorded by Ulrich. MacIvor found and analyzed several other distinct substances, and the crystallography of two of these, namely, hannayite and newberyite, was investigated by vom Rath (1878, 1879). MacIvor gives analyses of the guano free from these minerals (see table 39).

Much of the nitrogen, phosphate, and brown organic material was water soluble. MacIvor isolated from the solution sodium ammonium hydrogen phosphate or microcosmic salt, which is known from Peruvian and African guano as stercorite but which does not seem to have occurred as a mineral at Skipton. The minerals found in the guano are clearly characteristic of material of different water contents, struvite occurring alone in the very wettest, and newberyite and a nodular mineral in the driest. The other minerals appeared to characterize samples of intermediate water contents.

TABLE 39

	I	II	III	IV	V	VI
Water	16.74%	19.80%	30.52%	30.96%	33.50%	44.50%
Organic and volatile matter	22.00	52.83	44.98	31.21	44.66	32.60
N total	2.40	2.98	4.51	5.05	6.95	3.8
N nitric	0.39	(nearly all)	0.87	1.26	1.34	0.46
Ash	61.26	27.37	24.50	37.83	21.84	22.90
P ₂ O ₅ total	7.64	5.38	4.10	10.87	3.61	7.80

I. Light in color, containing newberyite and amorphous magnesium ammonium phosphate.

II. Sample of drier part typical of guano in which hannayite, newberyite, dittmarite, schertalite, and nodular magnesium phosphate occurred. Ash contained:

SiO ₂ (sol.)	1.06%
SiO ₂ and acid insol.	3.65
(Al,Fe) ₂ O ₃	5.23
CaO	2.00

MgO	0.58
Na ₂ O	2.93
K ₂ O	1.79
SO ₃	1.57
CO ₂	2.00
MnO	mere tr.

III-V. Rich brown with struvite and some hannayite.

VI. Brown black, full of struvite but no other minerals.

Struvite, Mg(NH₄)PO₄·6H₂O, occurred as large and often perfect crystals in the darker, wetter parts of the deposit. Analyses of the mineral from this deposit have been made (I) by Newbery (*in* Ulrich, 1870), (II) by MacIvor (1887), and (III) by MacIvor (1902a). They obtained:

	I	II	III	FORMULA REQUIRING
P ₂ O ₅	28.82%	28.81%	28.82%	28.98%
MgO	16.57	16.07		16.33
FeO	0.95	0.81	16.51	—
MnO	tr.	0.16		—
(NH ₄) ₂ O	54.49	{10.57	10.58	10.61
H ₂ O		{43.57	44.09	44.08

It is interesting that in this, as in the other guano minerals from Skipton, a small amount of Mg⁺⁺ is replaced not only by Fe⁺⁺ but also by Mn⁺⁺. The mineral loses water very slowly on exposure to the air and becomes covered with a white, powdery, dehydration product.

Hannayite, Mg₂H₂(PO₄)₂·MgH₂(NH₄)₂(PO₄)₂·8H₂O, occurred as fine colorless or slightly tinted prismatic crystals. It occurred frequently with struvite, though apparently was not found in the wettest parts of the deposit. Often hannayite crystals were found growing on those of struvite, but the former

mineral was most abundant in parts of the deposit which were apparently too dry to contain struvite, though a nodular, supposedly amorphous, magnesium ammonium phosphate, believed to be formed by the dehydration of struvite, occurred. Analysis gave:

		FORMULA REQUIRING
P ₂ O ₅	44.711%	44.63%
MgO	18.545	18.869
FeO	0.310	18.76
MnO	0.087	—
(NH ₄) ₂ O	8.095	8.10
H ₂ O (difference)	28.252	28.51

Schertalite, Mg(NH₄)₂H₂(PO₄)₂·4H₂O, described originally (1902a) under the preoccupied name muellerite, an error that was corrected in a later note (MacIvor, 1902b), occurred in the moderately dry (18%–25% H₂O) guano, as rather sparsely distributed flat crystals. Analysis gave:

	FORMULA REQUIRING
P ₂ O ₅	43.88%
MgO	12.28
FeO	0.20
MnO	0.05
(NH ₄) ₂ O	16.15
H ₂ O	27.55

Dittmarite, $\text{MgNH}_4\text{PO}_4 \cdot 2\text{Mg}_2\text{H}_2(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$, occurred in the drier parts of the guano, evidently often with the preceding mineral, as small rhombic crystals. Analysis gave:

		FORMULA REQUIRING
P_2O_5	46.51%	46.65%
MgO	25.87	26.28
FeO	0.38	—
MnO	0.08	—
$(\text{NH}_4)_2\text{O}$	3.94	3.42
H_2O	23.42	23.65

No crystallographic study seems to have been made.

Newberyite, $\text{MgHPO}_4 \cdot 3\text{H}_2\text{O}$, occurred primarily in the drier guano, and in the sample with the lowest water content it seems to have been the only well-defined crystalline mineral. Analyses gave:

		FORMULA REQUIRING
P_2O_5	40.73%	40.73%
MgO	22.37	22.99
FeO	0.85	—
MnO	0.206 ^a	—
H_2O (by difference)	35.84	36.31
		36.21

^a MacIvor (1902a) later gave 0.021% from the second analysis. It is not quite certain that the second of his analyses of either this mineral, or of hannayite, and analysis III of struvite are really independent of his earlier analyses of 1887. They may merely be recomputations using revised atomic weights. They are, however, described as "some later analyses" of the minerals in question.

As well as these minerals, MacIvor speaks of a nodular white amorphous material. He is uncertain whether or not it is to be regarded as a valid mineral species. It apparently occurred in all the drier samples and was evidently the material mentioned by Ulrich as forming white, earthy, nodular patches, with a composition similar to that of struvite but with less water. It was believed by both Ulrich and MacIvor to arise by the dehydration of the struvite. MacIvor, in his later paper (1902a), seems to regard this nodular mineral as $\text{Mg}_3\text{P}_2\text{O}_8\text{XH}_2\text{O}$. It is therefore not impossible that bobierrite occurred in the drier Skipton material.

NEW SOUTH WALES

JENOLAN CAVES

The deposits of this large group of caves in Paleozoic limestone have been described by Mingaye (1898a). The cave earth consists largely of red or white marl in part covered with a sediment described as drift and apparently of fluvial origin. A sample of reddish marl from a cave known as the Devil's Coachhouse yielded:

Hygroscopic H_2O	1.49%
Combined H_2O	3.01
SiO_2	63.41
Al_2O_3	18.02
Fe_2O_3	7.33
MnO	tr.
CaO	0.16
MgO	0.79
K_2O	5.09
Na_2O	tr.
P_2O_5	0.08
Organic	0.24

A white substance, light, porous, and friable, occurred in veins in the marl of Katie's Bower, part of the Left Imperial Cave. This material is said to be soluble in dilute HCl, though the second (II) of the two samples analyzed contains so much silica that it is hard to believe that this statement of solubility can apply to it. A nodular gray material (III), said merely to come from the Imperial Cave, has a similar composition to this sample.

	I	II	III
H_2O hygroscopic	33.60%	9.83%	6.79%
H_2O combined			3.52
SiO_2	0.70	50.10	54.13
Al_2O_3	26.83	13.88	15.13
Fe_2O_3	0.72	8.65	7.46
CaO	8.10	1.02	0.00
MgO	0.14	0.14	min. tr.
K_2O	0.09	1.35	1.69
Na_2O	0.00	tr.	0.87
P_2O_5	30.04	15.38	10.63
CO_2	0.15	0.12	—
Cl	min. tr.	—	—

No traces of F or SO_3 were found in I or II. There is said to be no indication of either bone breccia or bat guano in the cave.

In another cave, Grotto Cave, a deposit occurred under a hard layer of gypsum. This deposit is apparently the result of the action

of phosphatizing solutions on the limestone. Two samples gave the following analyses:

H ₂ O	16.82%	22.59%
SiO ₂	37.82	2.78
CaO	22.66	31.52
MgO	0.32	0.09
Al ₂ O ₃	0.64	0.10
Fe ₂ O ₃	min. tr.	0.00
K ₂ O	0.11	tr.
SO ₃	5.39	28.67
CO ₂	0.24	0.10
P ₂ O ₅	15.71	14.50

No fluorine and but a minute trace of chlorine were detected. Similar deposits, evidently mixtures of gypsum, calcium phosphate and sand, occurred in Bone Cave, Lucas Cave, and Woolshed Imperial Cave; again no guano or bone breccia was observed.

A white pulverulent substance from the Left and Right Imperial Caves is identified as minervite, i.e., taranakite:

H ₂ O at 200° C.	9.67%	9.50%
Loss 200°-red heat	18.23	18.19
Al ₂ O ₃	20.48	20.70
F ₂ O ₃	0.18	0.20
CaO	tr.	tr.
MgO	tr.	tr.
K ₂ O	8.89	9.01
P ₂ O ₅	40.86	40.83
Insol.	1.07	1.12

No F, Cl, or SO₃ was detected, but a trace of ammonia was present. Niter was detected in deposits of the Devil's Coachhouse.

Mingaye believed the phosphatic minerals of these caves to be derived from bones washed in when the marl and drift were deposited. It seems, however, as likely that ancient deposits of bat guano were involved.

MORUYA CAVES

Mingaye (1898b) gives two analyses of phosphatic deposits without any details of the occurrence. Carne supposes that the locality was at Bendithera:

P ₂ O ₅	27.80%	29.83%
CaCO ₃	3.29	8.18
N	2.45	0.363
Insol.	11.68	0.82

He also records, without locality, a bituminous-looking substance.

WELLINGTON CAVES

A group of caves in the Wellington Valley was discovered in 1830 by Sir Thomas Mitchell (1839) who found in addition to a red cave earth and well-developed stalactites and stalagmites several deposits of bone breccia. These deposits yielded a large number of bones of various extinct marsupials (Owen, 1877). The presence of phosphatic material other than in the bone breccia, where it is not necessarily of excretory origin, is indicated by Carne (Carne and Morrison, 1919) who states that attempts were made to exploit phosphate in the region of the caves in 1913. The material apparently occurred as white nodules in the cave earth, or scattered about the surface, probably in the region of collapsed caves. The best specimens contained:

P ₂ O ₅	34.20%
CaCO ₃	6.46
(Al,Fe) ₂ O ₃	<5.0
Earthy gangue	4.50

BORENORE CAVES

At a cave called Little Borenore a very small deposit of hydrated phosphate of aluminum containing 35.15% P₂O₅ was discovered. The calcareous deposit of the walls contained up to 4.18% P₂O₅.

GAMBOOLA CAVES, MOLONG, ASHBURNHAM

A small amount of phosphorite containing up to 29.53% P₂O₅ is recorded.

It is not unlikely that a number of other caves in New South Wales and other parts of Australia that have yielded fossil bones also contained phosphate of excretory origin. The literature of these localities is difficult, though Simpson (1932) has provided an indispensable guide to its exploration. It is, however, improbable that any of the numerous notes and papers that have not been examined in the present study would add anything important to our knowledge of chiropterite or similar deposits in Australia.

SOUTH AUSTRALIA

Among the localities recorded by Jack (1919) as having been licensed for guano exploitation, the caves on Burr Creek, Moolooloo Run, perhaps the locality designated

Patsy's Springs, Moolooloo Run, and the caves north of section 115, hundred of Rivoli Bay, may have contained bat guano.

WEST AUSTRALIA

Woodward (1912) reports that in the Jingemia Cave, 8 kilometers northwest of Watheroo, guano containing up to 8.73% P_2O_5 and up to 11.21% N occurred on the floor and was produced by bats, whereas bird guano containing 5.48% to 7.41% P_2O_5 and 10.06% to 23.88% N was present on rock

ledges. A locality called Bishops Hole produced guano containing 9.83% to 12.90% P_2O_5 and 0.25% to 6.21% N.

NEW ZEALAND

Morgan (1915) records cave guano at Akaroa and at Onetana, Collingwood District, South Island. He also indicates that a hydrous phosphate of aluminum with a little ammonium phosphate occurs in a cave near Flaxbourne, Marlborough, South Island. This last occurrence suggests taranakite.

CAVE GUANO IN TROPICAL ASIA

Bat guano evidently occurs in caves throughout the whole of the mainland of southeastern Asia and the Indonesian islands. The available accounts are inadequate and certainly do not embrace all the regions where deposition has occurred. Very little has been recorded as to the guano bats actually producing deposits in the region, but from Pryer's (1884) fascinating account of caves near Elopura in Borneo it is known that at least in one locality a species of *Nyctinomus* is responsible.

NEW GUINEA

According to Hutchinson (1941) bat guano is found in many caves in New Guinea. A partial analysis of a superficial part of the deposit in a large cave, inhabited by a small species of bat, in the Madang District is given and is here reproduced:

P_2O_5	8.9%
CaO	4.3
K_2O	0.9
N	3.7

NEW IRELAND

Hutchinson (1941) describes a cave in limestone at Kaut on the west coast of the island. The entrance is about 21 meters above sea level on a marine cliff. The cave consists of an outer chamber in semidarkness, a completely dark inner chamber, and numerous small subsidiary grottoes. It is nearly 400 meters long and contains pools of water, stalactites, and stalagmites. It is said to be inhabited by "large numbers of bats varying in length from 2 to 10 inches, rats, snakes and insects." The moist and slippery guano,

which in places was several feet deep, varies in color from black to light brown.

The material from the outer chamber contained about 16% P_2O_5 and 26% CaO; that from the other parts of the cave is said to have contained up to 43% P_2O_5 , but with only 1% to 2% CaO. This material is supposed to be aluminum and iron phosphate. The following figures give the ranges for the various constituents that were determined on air-dried samples:

H_2O (moisture)	14.3-21.5%
Ignition loss	8.4-38.2
Insol. in HCl	7.3-11.2
Sol. in HCl	38.3-62.1
P_2O_5	14.6-43.1
CaO	1.3-26.2
K_2O	0.2- 4.1
N	0.1- 3.2

BORNEO

Everett (1880) examined 32 caves in Borneo, two being on Mt. Sobis up the Niah River (about latitude $3^{\circ} 40' N.$, longitude $114^{\circ} 00' E.$) and the remainder in upper Sarawak. He was primarily interested in the possibility of finding fossil human remains and, not having been successful in this, his account of the stratigraphy is not sufficiently specific. The caverns examined are said to have been tunnel, fissure, and ordinary ramifying caves. A few contained nothing but thick accumulations of bat or bird guano which yielded a few remains of bats and swifts. Other caves contained a tenaceous, dark yellow, homogeneous clay. Caves at both Jombusan and Niah "about 40 ft. above the flat land at the bases of the hills" showed a

characteristic stratification which seems to have been essentially identical, even though the two groups of caves are remote from each other.

I. Surface layer of disturbed earth, charcoal, rotting wood and bamboos, with modern pottery, glass beads, recent bones, and freshwater shells; the artifacts clearly were left by Dyaks who camp in the caves when collecting edible birds' nests three times a year.

II. Talus largely composed of angular blocks of limestone with loam or clay mixed with earthy carbonate of lime, which locally forms a hard concrete, recent shells, and bones, mainly of rodents.

III. River mud mingled with bat guano with rounded masses of limestone and creamy crystalline stalagmite incrustation. This layer is full of bat remains, associated with bones of large mammals of recent genera. The bones are broken and water worn. Fish bones and scales, chelonian, crustacean, land and freshwater molluscan remains and leaves also occurred. Artifacts are apparently found in the upper part of this layer but are inadequately described.

IV. A yellow clay more or less concreted into hard pseudostalagmite, with bones and teeth of pigs. In the case of cave XIII this layer is separated from layer III by a pure stalagmite layer.

It seems probable that the transition from IV to III represents the inception of a wet period, while II may represent a drier period than prevails today. The whole problem presented by these caves evidently needs reinvestigation.

Pryer (1884) gives a detailed account of remarkable caves at Goinanton, about 32 kilometers inland from Sandakan (Elopura) in British North Borneo. The caves penetrate a limestone scarp apparently composed of elevated reef rock about 300 meters high. Most of them intercommunicate. The lower, large cave, Simud Itam, has a large vent or chimney opening near the mouth of the main upper cave, Simud Putih. The caves are inhabited by enormous populations of the bat *Nyctinomus plicatus* (Buchanan) and the edible-birds'-nest bird, *Collocalia fuciphaga* (Thunberg). The bat population appeared mainly to occupy the lower Black Cavern or Simud Itam, the birds mainly the upper

White Cavern or Simud Putih. Much bat guano, at least 4.5 meters thick, existed in a branch of the upper cave with a separate entrance.

At about 5 P.M. (March 20, 1884) the bats began to leave the lower cave, coming out in wheeling columns from the top of the chimney. A little later, at 5.45 P.M., the swifts began to return to roost, entering the upper cave; the beating of their wings made a noise like a strong gale in the rigging of a ship. This continued till after midnight. The bats returned and the swifts went out before daybreak the next morning. A pair of kites, *Haliastur indicus*, and several specimens of the hawk *Machirhamphus alcinus* were observed catching bats in the evening. The latter bird, with a small beak and wide gape, was observed catching swifts on their way out in the morning, though at night it seemed less successful in obtaining the birds than the bats. Its behavior in feeding on the latter is described as like a man swallowing oysters. Pryer believed that the *Collocalia* nests were built by the bird of a material thickly encrusting damp rocks like half-melted gum tragacanth, which proved (Murray in Pryer) to be masses of a species of *Gleocapsa*. Murray noted that a species of the same genus formed a thick coating on the walls of a marine cave north of Arborath in Scotland, where it may well have been fertilized by the droppings of pigeons, presumably wild rock doves, *Columba livia*. It is, however, certain that Pryer was in error in his belief that the edible nests were derived from the dying masses of the alga. Green (in Pryer) correctly points out that nest material appears to be a mucin-like substance. The total population of birds and bats in the caves must be enormous; the annual yield of nests was given as \$25,000. The best nests sold in packets of about 40 at \$9 per packet. This implies that rather over 100,000 nests were collected annually. Actually the total number taken must have been considerably greater, as part of the revenue was derived from poor nests, selling at a lower price. In spite of the continual disturbance of the population no reduction in the number of *Collocalia* seems to have taken place. Pryer's description of the interiors of the caves, with rattan ladders and stages set on apparently inaccessible ledges, is reminis-

cent of Piranesi's "Carcere." No attempt to use the guano appears to have been made at the time of his visit, though the quantity present is said to have been enormous.

Further deposits are recorded (Minenbureau, 1928) from Dutch Borneo in caves on Gng Hapoe, a mountain in the district of Riam Kanan and Kiwa, in southeast Borneo, where the guano is said to reach a thickness of 2 meters, and at Gng Lampinet, southeast of Rantau, Benoea Ampat, where the reserve was put at 10,000 tons.

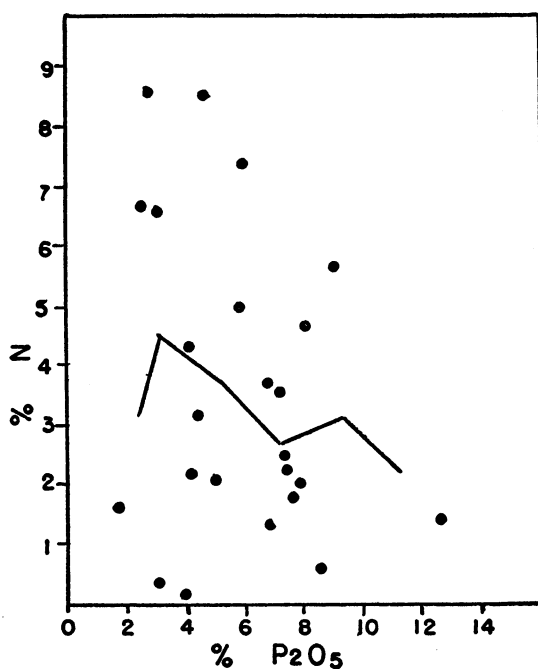


FIG. 87. Relationship of total nitrogen to phosphate in Philippine guanos.

THE PHILIPPINE ISLANDS

According to Cox (1912) virtually every cave in the archipelago contains bat guano, in layers from a few centimeters to over a meter in thickness. He gives a number of analyses, mostly from unspecified localities. Where there are total nitrogen and total phosphorus determinations, these analyses have been used to construct figure 87. A few localities are specified, and the determinations given in table 40 relate to these.

Aso (1940) says that the Philippine deposits were the most extensive in the world.

He gives the following ranges for Montalban guano from Luzon:

H ₂ O	9.27-11.83%
N total	1.71- 8.49
N·NO ₃ ^a	0.61- 1.44
N·NH ₃	0.12- 0.29
P ₂ O ₅ total	7.30-14.97
P ₂ O ₅ water sol.	0.34- 0.78
K	0.65- 0.79
(Al,Fe) ₂ O ₃	4.49- 5.58

^a As sulphate (*sic*).

He quotes Hardy, whose paper has not been traced, as indicating that fresh droppings contained 60% water and says that he confirmed this on Luzon and Bohol material. He gives some details about the locality studied on the last-named island.¹

FILOMENA CAVE, BOHOL

The cave apparently opens at an altitude of about 50 meters above sea level, is about 600 meters long, 10 to 32 meters wide, and 20 meters high. Stalactites are apparently well developed. Thousands of small bats hang from the roof of the cavern, the rock floor of which has been phosphatized to a depth of 30 feet. Aso gives no estimate of the mass, but in another section he indicates that the Philippine deposits are the largest in the world. Since he mentions otherwise only the Montalban Cave with about 3000 tons and several other unspecified caves in which the deposits are on a small scale, it would seem likely that the deposit in the Filomena Cave was believed to be very large. Aso gives the analyses here reproduced as table 41.

JAVA

Numerous limestone caves containing guano are said to exist, as in Gng Pawon, a mountain near Padalarang, where small quantities of bat guano are regularly exploited by the local population (Minenbureau, 1928). An analysis of Javanese bat guano is quoted by Binaghi (1909) from Marco Soava, "Chimica vegetale ed agraria" (p. 373), which it has not been possible to

¹ Since the above was written, an abstract of a paper by Irving and Teves (1947) has become available, in which deposits of 10,000 to 15,000 tons are described at Pupug, Bohol, and previous analyses of guano from this island are summarized.

TABLE 40

	H ₂ O	N Total	N·NH ₃	P ₂ O ₅ Total	P ₂ O ₅ Water Soluble	Citrate Soluble	K ₂ O	CaO
Batangas, Luzon	—	8.51%	—	4.28%	—	—	—	—
Batangas, Luzon	0.00	5.69	—	8.85	—	—	—	—
Inlalapid Cave, Norzagaray, Bulacan, Luzon	—	1.31	—	6.73	—	—	—	—
Montalban, Luzon	9.54%	2.01	—	7.68	—	—	—	—
Mina Caridad, Monte Luboe, Montalban, Rizal (<i>sic</i>)	23.2	—	5.58%	—	3.76%	—	—	—
Kapuluan I., Tayabas, Luzon	45.40	—	0.22	6.05	0.18	—	—	—
Marinduque I.	15.38	3.52	—	7.06	—	—	0.92%	2.69%
Isabela I. (not over 100 tons)	—	—	0.86	1.40	—	—	0.73	—
Kahoagan I., north of Samar	—	—	3.98	12.88	—	—	1.08	—
Cave near Pilar, Capiz, Panay	—	2.13	—	4.07	—	—	—	—
Cave near Pilar, Capiz, Panay	—	1.72	—	7.58	—	—	—	—
Guimaras	1.43	—	—	12.50	2.30%	4.80%	1.53	—
Guimaras	19.51	2.08	—	4.84	—	—	1.29	6.60
Guimaras (2000 tons)	60.78	—	1.79	—	1.75	—	0.98	—
Dingle, Guimaras	—	—	—	23.12	—	—	—	—
Dingle, Guimaras	—	—	—	18.20	—	—	—	—
Calapan, Mindoro	9.30	2.26	—	7.31	—	—	0.67	—
Calapan, Mindoro	7.68	1.55	—	1.58	—	—	0.65	—

consult but which is unlikely to be a primary source.

H ₂ O and organic	79.40%
N total	7.20
P ₂ O ₅	3.40
K ₂ O	1.70

SUMATRA

A few deposits are recorded (Minenbureau, 1928), namely, at Lijang na Moewap, in the district of Padang Lawas (Tapanoei), at Benkoelen, south Sumatra, on the island of Kloewang off the west coast of Atjen, north Sumatra, and on the island of Minadanaoe, in the Tambang group. It is probable that many other small deposits exist or have existed.

INDO-CHINA

While the phosphorites of Indo-China appear in general to be of hydrothermal origin and of considerable complexity, Dupouy (1913) has indicated the presence of both phosphate and nitrate in cave earths derived from bat guano. Innumerable caves in the calcareous massif of Indo-China have yielded nitrate, which was mainly used in pyrotechnics. Dupouy indicates that 21 localities were

exploited in the provinces of Lang-Son, Tuyen-Quang, Thai-huyen, Bar-hink, and Hung-Hoa under the Emperor Tu-Duc. The material extracted is described as calcareous earth impregnated with bat guano. The exploitation was regulated very stringently. In modern times the inhabitants of remote places have been encouraged to use "cet anodin salpêtre" in the manufacture of fireworks "temoins bruyants et indispensables des jours heureux."

In many cases niter is said to be associated with nitrocalcite, brushite, and phosphorite. Brushite is specifically recorded from Ham-Ron, region Thanh-Hoa, Annam, associated with calcite, dolomite, and phosphorite, and from a cave at Van Link, region of Sang-Son, associated with calcite, dahllite, collophane, and nitrocalcite. The brushite at the latter locality formed crystalline translucent crusts, 5 to 6 cm. thick, giving on analysis:

CaO	31.6%
MgO	2.3
Fe ₂ O ₃	0.8
Al ₂ O ₃ , SiO ₂	0.6
P ₂ O ₅	38.3
CO ₂	3.4
H ₂ O	23.1

TABLE 41

	N Total	N · NH ₃	N · NO ₃ ^a	P ₂ O ₅ Total	P ₂ O ₅ Water Soluble	P ₂ O ₅ Citrate Soluble	K ₂ O Total	(Al,Fe) ₂ O ₃	CaO	Sand
	%	%	%	%	%	%	%	%	%	%
Filomena Cave, Bohol:										
Fresh guano	6.66	—	—	3.88	—	—	0.83	12.81	—	—
Old guano	3.90	—	—	12.92	—	—	0.75	5.79	—	—
White, powdery rock phosphate	0.25	—	—	35.61	—	—	—	9.00	—	—
Brown, powdery rock phosphate	0.14	—	—	27.31	—	—	—	38.70	—	—
Bohol, locality unspeci- fied:										
Fresh deposits	8.31	1.12	0.72	6.48	0.82	3.45	1.60	7.97	0.52	—
Ordinary deposits	3.90	0.08	0.78	12.93	1.69	5.00	1.18	5.79	—	—
Clay deposits	4.11	0.12	0.58	12.84	2.00	2.92	—	30.53	13.25	5.63

^a Sulphate (*sic*).

MALAY STATES

A few analyses have been published by Voelcker (1878a), and by Dunstan (1905). Greenstreet (1926) states guano occurs in caves in limestone hills from the Malay States through Siam to the Shan States. He gives a number of proximate analyses. Of these the

total N and P₂O₅, when both were determined, are plotted in figure 88. In the analyses given by Dunstan the nitrate nitrogen has been added to the so-called total nitrogen. Such notes on the occurrences as are given and the more significant analyses are reported below.

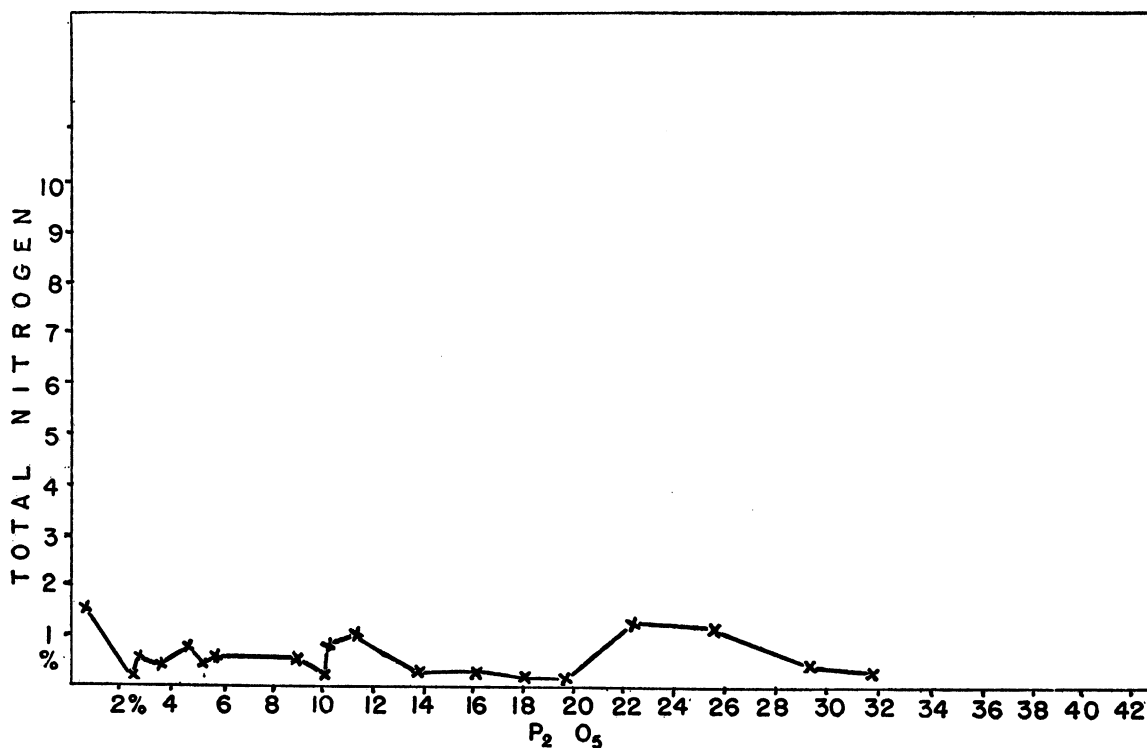


FIG. 88. Relationship of total nitrogen to phosphate in Malayan guanos.

SELANKOR

The most important deposit was in the Batu Caves, while an insignificant amount occurred in a granite cave at Gap. Three analyses of material from the Batu Caves are given by Dunstan (1905):

	I	II	III
H ₂ O (moisture)	21.26%	22.92%	26.60%
H ₂ O (combined)	2.91	2.62	2.24
Organic matter	6.57	17.21	9.62
Total N	0.81	1.52	0.84
SiO ₂	31.62	19.79	21.77
Al ₂ O ₃	11.36	10.78	10.70
Fe ₂ O ₃	11.03	9.05	8.28
MnO	0.20	0.19	0.13
CaO	1.81	1.86	2.32
MgO	1.03	1.04	0.95
CuO	0.37	0.35	0.34
K ₂ O	1.12	0.88	0.88
Na ₂ O	0.78	0.75	0.79
NH ₃	0.12	0.14	0.12
N ₂ O ₅	0.81	0.91	0.86
P ₂ O ₅	8.60	10.86	14.17
P ₂ O ₅ citrate sol.	7.38	8.54	9.75
SO ₃	0.41	0.53	0.50
Cl	tr.	tr.	—

- I. Earthy reddish brown powder, 0-3 inches.
- II. Dark brown earthy powder, depth of 6 inches.
- III. Light yellowish brown powder, depth of 1 foot.

The locality is said to be a series of limestone caverns. In view of this the high silica and sesquioxide contents apparently indicate that the material is a residual soil mixed with leached guano. The high copper contents are very extraordinary, but not unique (p. 456).

Greenstreet gives the following determinations:

	BATU, 1922 SURFACE	BATU, 1922 2 FEET	BATU 4 FEET	GAP
Moisture	6.0 %	0.8%	2.7 %	3.4 %
Ignition loss	11.4	5.7	19.0	18.4
N total	0.97	0.21	0.38	—
N·NO ₃	0.55	0.00	0.00	—
P ₂ O ₅	11.25	2.50	3.56	2.05

PERAK

Dunstan gives an analysis of bat guano from limestone caves at Padang Rengas, 16 miles from Taiping. The material is said to have consisted of small lumps mixed with powder. It was dark buff in color, but con-

tained white fragments of calcium sulphate and phosphate.

H ₂ O moisture	9.59%
H ₂ O combined	4.36
Organic matter	4.88
Total [sic] nitrogen	2.47
SiO ₂	8.42
Al ₂ O ₃	2.56
Fe ₂ O ₃	1.75
MnO	0.31
CaO	22.27
MgO	tr.
CuO	0.34
K ₂ O	2.01
Na ₂ O	1.30
NH ₃	0.58
N ₂ O ₅	7.55
P ₂ O ₅	17.52
P ₂ O ₅ water sol.	0.81
P ₂ O ₅ citrate sol.	3.25
SO ₃	16.32
Cl	0.13

The high copper content is comparable to that of the Batu samples. The specimen appears to contain less residual material and more calcium salts derived from alteration of limestone than do the bat guanos from Batu.

A deposit (I) of unknown depth from a cave at Gugong Tunggal and a deposit (II), which seems to be very impure, from Batu Kurau, Larut, were analyzed by Greenstreet:

	I	II
Moisture	8.5%	21.3%
Ignition loss	20.7	26.7
N total	0.5	1.5
P ₂ O ₅	5.7	0.5

A limestone cave at Gunong Pondok, Padang Rengas, was found to contain a re-

markable deposit of bat guano. The limestone in which the cave is situated is largely crystalline. The cave is about 600 feet deep and 25 feet wide and is inhabited by a vast number of bats. The floor of the mouth of the cave is covered to a considerable depth with choco-

late-colored earthy matter. In the interior of the cave the limestone of the floor loses its crystalline character as it comes in contact with the bat guano.

The most remarkable feature of this deposit is the high nitrate content of some of the samples. Unfortunately total nitrogen was not determined. Nitric nitrogen was undetectable in 16 out of 24 samples analyzed, but in some of the other samples nitrate was evidently a major constituent. The analyses

ble deposit exists at Kapong Reman, Kuantan. Two specimens of material from a depth of 6 feet were analyzed:

	DARK	LIGHT
Moisture	18.9%	25.3%
Ignition loss	22.1	22.3
N (total)	0.73	0.41
P ₂ O ₅	4.7	5.2

PERLIS

There are reputed to be a hundred caves

TABLE 42

No.	Description	Moisture	Ignition Loss	N·NO ₃	P ₂ O ₅
4	Dark brown powder	9.4%	35.2%	0.0	19.0%
5	Yellow powder	19.7	13.8	0.0	23.0
7	Black powder	15.6	25.8	0.0	24.0
9	Light brown powder	16.1	5.8	0.0	31.0
10	Dark brown powder	21.7	22.0	0.0	15.0
11	Yellow powder	19.2	8.7	0.0	30.0
13	Soft rock	8.1	8.1	0.0	36.0
14	Hard rock	0.0	39.5	0.0	3.5
15	Hard rock	0.0	16.5	0.0	28.0
16	Hard rock	0.0	21.5	0.0	2.4
17	Rock crystals	0.0	34.9	0.0	17.0
18	Brown powder	9.2	18.2	0.0	20.0
19	Gray powder	8.0	8.1	0.0	34.3
20	Brown powder	15.0	10.4	0.0	19.2
23	Black powder	10.9	15.3	0.0	33.0
24	Metamorphosed limestone	11.7	5.1	0.0	30.4
8	Black powder	10.3	41.7	1.1%	15.0
12	Soft rock	18.5	14.8	1.6	14.5
3	Black powder	13.5	21.7	1.8	24.0
1	Brown powder	18.9	55.8	1.9	5.5
2	Brown powder	15.8	46.3	2.1	12.0
21	Fresh and sticky	24.6	deflagrated	3.1	10.0
22	Very fresh sticky	42.2	deflagrated	4.0	19.0
6	Dark brown powder	16.0	29.1	7.0	18.0

are here rearranged (table 42) according to the nitrate content. No indication of the position of origin is given; possibly specimens with low sample numbers came from near the entrance.

It appears from the statement that a sample from 8 feet below the surface contained 20% P₂O₅ that no. 18 came from this depth. The very high nitrate content of the fresh guano is interesting; most samples have evidently lost nitrate, but no. 6 is presumably enriched.

PAHANG

A cave apparently containing a considera-

in this state containing an aggregate of 50,000 to 1,000,000 tons of guano. Two large caves are briefly described by Greenstreet. Goa Mempi, a cave 200 feet in length and 50 feet in width, is covered with a fairly dry, soft, powdery guano 3 to 20 feet thick and varying from chocolate to buff in color. The cave contains few bats, and the deposit is evidently not of contemporary origin. Goa Sammy is a larger and very complex cave. The deposit is darker and deeper red and more lumpy than that of Goa Mempi. It varies in depth from a mere film to at least 10 feet. A large part of the guano is covered

TABLE 43

	Moisture	Ignition Loss	N Total	P ₂ O ₅ Total	Insoluble
GOA MEMPI					
White powder, 40 feet from entrance, depth of 4 feet	5.3%	11.0%	1.1%	25.6%	23.6%
Surface, 40 feet from entrance	10.5	9.1	0.2	32.0	12.2
Surface, 50 feet from entrance	8.1	18.4	1.2	22.3	15.1
Pocket	6.6	11.2	0.5	9.0	42.7
Pocket	11.9	9.2	0.0	2.1	42.6
Pocket	3.1	3.6	0.1	18.2	2.5
Small boulders	2.5	17.6	0.2	16.4	10.9
Back of cave, chocolate-colored powder, 6-9 inches in depth	11.0	18.6	n.d.	15.2	12.8
Puce-colored deposit	2.6	23.1	n.d.	11.7	28.6
Brown rock wafers, middle of cave	5.4	17.2	n.d.	12.6	20.4
Gray powder with lumps, middle of cave, depth of 20 feet	7.2	14.0	n.d.	23.7	17.0
Brown powder with lumps, honeycomb structure	9.3	8.3	n.d.	25.4	13.1
Brown powder, bulked sample	5.4	14.7	n.d.	19.6	17.0
GOA SAMMY					
Soft and lumpy, flowing down gully	19.8	23.4	—	22.5	16.9
Cave wall, reddish brown powder	11.6	13.6	—	22.8	26.0
Light brown powder, under 1-inch rock crust	4.4	26.7	—	18.7	19.1
Light brown, wafery rock, overlying the "dirty white, honeycombed rock," listed below	2.7	21.8	—	36.0	4.4
Light brown powder with hard lumps, adjoining the "light brown powder under 1-inch rock crust," listed above	5.0	18.2	—	28.9	24.7
Chocolate-colored powder with hard lumps, center of cave, 18 inches deep	5.1	31.7	—	20.0	28.2
Dirty white, honeycombed rock	5.0	16.8	—	13.2	38.8
Brown powder with hard lumps, below the "light brown powder with hard lumps," listed above, at depth of 2 feet	10.2	19.4	—	19.3	34.5
Dark brown powder with hard lumps	10.0	13.0	—	16.4	23.8

TABLE 44

	Moisture	Ignition Loss	N Total	P ₂ O ₅ Total	Insoluble
ATTIE					
Soft brown lumps, 25 feet from cave mouth, depth of 4 feet	19.8%	20.1%	0.5%	2.6%	39.7%
Brown powder, 70 feet from cave mouth, depth of 4 feet	8.4	14.7	0.1	19.7	31.9
Brown powder, middle of cave, depth of 4 feet	5.5	15.8	0.3	13.7	21.0
Soft gray powder, back of cave, depth of 3 feet	11.2	16.9	0.2	10.1	30.7
CAMPBELL					
Dark red powder, inner chamber surface	10.9	9.2	tr.	12.8	29.8
Puce-colored powder, outer chamber surface	7.3	10.9	tr.	8.1	49.4

with a crust, 2.5 cm. thick, of phosphatic rock. Though there are a fair number of bats in the cave, there is very little fresh guano. The analyses from these caves that are available are given in table 43. It is unfortunate that no nitrogen determinations were made on the Goa Sammy deposit.

Greenstreet gives analyses of material from two other caves in the state of Perlis, without further comments; these analyses are given here in table 44.

BURMA

Thompstone (1909) states that considerable deposits of bat guano occur in limestone caves in the range of hills bordering on the Shan States and dividing them from the plains of the Irrawaddy, and also near Mul-

mein, and Tavoy and in other parts of the Tenasserim division. In one place near Kyaukse, the material is said to be "several hundred feet" deep, filling a broad cleft between rocks, rather than a cave. In the vicinity of Mulmein and Tavoy, the guano was used to fertilize durian and other fruit trees. Thompstone gives the following analyses of dry material from Kyaukse:

Organic and combined H ₂ O	72.00%	47.15%	28.06%
Total N	7.97	4.37	0.63
P ₂ O ₅	2.13	1.06	1.62
K ₂ O	0.76	0.68	0.59
CaO	7.89	1.23	1.68
MgO	1.55	1.06	0.98
Fe ₂ O ₃	2.02	2.35	3.90
Sand	13.89	45.34	63.43

CAVE GUANO IN AFRICA

Bat guano probably occurs wherever caves are found throughout the greater part of Africa, except in deserts. It is convenient to divide the occurrences into those of temperate South Africa, of central Africa, of Madagascar and the Mascarene Islands, and of Palearctic North Africa, including Egypt.

SOUTH AFRICA

TRANSVAAL

Ingle (1905) has described deposits of bat guano in caves on the farm Wonderfontein near Oberholzer Station between Krugersdorp and Potchefstroom, Transvaal. The

material, consisting largely of bat excrement, varied in depth from about 1.5 to 6 meters. Interstratified with the bat guano were layers consisting largely of the dung of "wolves," presumably actually hyenas.

Some deposits contained numerous bones, referred to oxen, antelopes, "wolves," jackals, etc., with an occasional human bone. Some of the caves had probably been inhabited by lions who had brought their prey back to their dens. The most notable deposit of "wolves'" dung lay under bat guano and silt and over a layer in which fragments of charcoal were found and which was supposed to be ash. The supposed bat guano appears

TABLE 45

	I	II	III	IV	V
H ₂ O (moisture)	3.26%	9.32%	2.78%	5.63%	4.00%
Ign. loss	6.78	9.02	6.10	30.49	28.80
Total N	0.19	0.32	0.27	1.56	2.53
K ₂ O	0.21	0.05	0.67	1.14	0.19
CaO	0.37	33.14	14.95	14.54	7.28
(Al,Fe) ₂ O ₃	7.73	—	—	—	—
P ₂ O ₅ total	1.71	26.55	9.02	1.58	2.26
P ₂ O ₅ sol.	—	6.00	—	—	—
Insol. (sand)	77.06	14.87	62.46	32.67	47.35

- I. Bat guano from large cave.
 II. "Wolf" dung from cave near tent.
 III. Ash apparently from below II.

- IV. Western cave containing many bones.
 V. Recent deposit in cave with vertical entrance.

to have been very greatly contaminated with silt. Analyses are given in table 45. It is evident that the only deposit that is primarily of biological origin is II, the "wolf" dung layer, which consists largely of calcium phosphate.

Ingle (1913) gives several other analyses of Transvaal guano:

	I	II	III
N	1.50%	6.20%	9.70%
P ₂ O ₅	2.82	7.40	3.81
CaO	—	0.80	—
K ₂ O	0.78	—	1.29

I. Potchefstroom.

II. Elandsfontein.

III. Zoutpansberg.

ERMELO

A deposit of bat guano in a cave near Ermelo is noted by Marchand (1918). In the guano small soft white or yellow nodules of an aluminum phosphate were present. Analyses of this material appear to correspond to:

	I	II
Al ₂ O ₃	19.22%	15.8%
Fe ₂ O ₃	—	tr.
P ₂ O ₅	53.58	55.6
H ₂ O	27.16	28.4

It is evident that the white nodular mineral represents an acid aluminum phosphate not otherwise recorded. If any material still exists, a reëxamination would be of interest.

CENTRAL AFRICA

Bat guano appears to be known from several widely separated localities in East Africa, but only one geochemically adequate account has been published. In addition to this account, which deals in detail with one locality in Tanganyika Territory and gives notes on three deposits, two partial analyses have been published.

	CAVE EARTH, MOZAMBIQUE (HUTCHINSON, 1941)	BAT GUANO, EAST AFRICA (ANON., 1936)
P ₂ O ₅	10.92%	16.26%
CaO	2.42	—
K ₂ O	0.35	0.85
N	0.81	1.22

A considerable amount of biological informa-

tion is, however, available about certain other localities discussed below.

SUKAMAWERA, SONGWE RIVER

LATITUDE 80° 54' S., LONGITUDE 33° 13' E.

The best-known locality is in the Songwe River area in the extreme southwestern part of Tanganyika Territory (Teale and Oates, 1934). A group of caves has been formed in a limestone of unknown but geologically not great age. This limestone is possibly deposited by hot springs. A few such springs exist in the vicinity, and formerly they may have been more extensive. The lime may be derived from resolution of lacustrine limestones.

The main cave is near the village of Sukamawera, on the west side of the Songwe River, 12½ miles west-southwest of Mbeya Peak and 8½ miles south of Punguluma, the northwestern end of the Mbeya Range. It is apparently at least 1 kilometer long and though dry is said to contain a pool of water in its innermost recesses.

Countless bats inhabit the cave and have deposited a considerable thickness of guano which has interacted with decomposing limestone to a thickness of about 5 to 7 meters. The surface material is fresh moist bat dung, lying over a coarse brown powder, consisting mainly of organic matter, with abundant wing sheaths of small insects; small fragments of partly phosphatized limestone are also present. At a greater depth the material varies in color from cream to pale brown and banded, is coherent but very friable. This material contains much less organic matter than the brown powder but may contain up to 33% P₂O₅.

Two analyses are given, I referring to an average sample from a profile 0 to 16 feet deep, II to material from the bottom of the profile:

	I	II
H ₂ O at 100° C.	9.8%	10.6%
Loss on ignition	34.5	24.9
N total	4.1	2.4
Ash	55.7	64.5
CaO	14.3	7.0
K ₂ O	0.6	0.5
P ₂ O ₅ total	11.8	19.1
P ₂ O ₅ water soluble	0.4	0.6

The lower layers presumably contain aluminum phosphate.

In addition to these analyses Teale and Oates give five determinations by Milne, of total nitrogen and phosphate in bat guanos from three other localities in Tanganyika Territory:

	N	P ₂ O ₅
Amboni, Sigi River, surface	5.2%	0.17%
Amboni, Sigi River, 1 meter	0.3-0.6	1.6-2.0
Amboni, Sigi River, >1 meter	1.4	2.0
Ukinga	10.2	5.4
Kilwa	5.4	5.9

KULUMUZI OR TANGA CAVES

Seven kilometers west of Tanga, Tanganyika Territory (also erroneously referred to as Sigi Caves). Three remarkable caves have been studied by several zoologists whose results are summarized by Jeannel and Racovitza (1914). Only two of the caves, designated A and C, contained bats. In the case of the latter cave only flying foxes (*Cynonycteris collaris* Illiger and *C. sjöstedti* Lönnberg) occurred, hanging in a passage, near its entrance into a partly illuminated hall with several apertures in its roof. Guano is said to have been present below this bat colony and large cockroaches of the genus *Gyna*, a number of beetles (*Somoplatus substriatus* Dejean, *Tribatus cavernicola* Lewis, *Alexia* sp.), isopods, spiders, and tineid moths inhabited the deposit. The cave designated as A extends from about 150 meters inward from its entrance. In the middle is a large chamber containing a big colony of Microchiroptera, identified as *Triaenops afer* Peters, *Megaderma frons* Geoffroy, *Nycteris hispida* Schreber, *Coleura afra* Peters, *Taphozous mauritanus* Geoffroy, and *Nyctinomus limbatus* Peters. A thin layer of guano covered the chamber. The guano was frequented by *Somoplatus substriatus*, *Somotrachus elevatus* Fabricius, *Tribatus cavernicola*, *Alexia* sp., Diptera, the proctotrupid *Antroscelio lucifugax* Kieffer (probably parasitic on tineid moths), the cockroaches *Gyna vetula* and *G. kazungulata*, and mites. Unfortunately no analyses are available, but the extremely rich fauna would be expected to reduce the organic matter in the deposits more rapidly than occurs in less tropical and less frequented caves.

ZANZIBAR

Jeannel and Racovitza (1914) indicate that a small amount of guano was present in the Haïtajwa Cave and the Manapwani Cave in the island of Zanzibar.

SHIMONI, KENYA COLONY

Two caves at Shimoni, 60 kilometers south of Mombasa, were studied by Alluaud and Jeannel (Jeannel and Racovitza, 1914). The cave designated A was an irregular gallery in coralline limestone just above sea level. The cave is entered from a row of holes in the roof. Northwest of these entrances a passage gives access to a gallery 30 meters long inhabited by innumerable bats. Guano bathed with water of a small underground lake covers the floor. The water fertilized by the guano contained an excessively rich crustacean fauna, compared to grains of tapioca in soup and composed of the amphipod *Quadrivisio bengalensis* Stebbins and the cirolanid *Anina lacustris* G. Budde Lund. Many terrestrial isopods, beetles, crickets, and cockroaches lived on the emergent heap of guano. Another smaller heap of guano had been deposited at the opposite end of the cave in a dark chamber which, though moist, apparently had no pools of water on the floor. This heap of guano was alive with tineid larvae and was frequented by innumerable mites, Coleoptera, and giant cockroaches (*Gyna kazungulata* Giglio-Tos).

In the second cave, designated B, a small chamber opening towards the sea was filled with bats. In pools Crustacea occurred in great numbers as in the other cave, while enormous cockroaches swarmed over the walls and floor so that the entire chamber appeared alive.

These caves are of interest in showing that under damp tropical conditions a guano deposit formed by bats can support a quantitatively rich fauna that must play a considerable part in the diagenesis of the deposit.

CAMPBELL CAVE

Above Burgurett, west Kenya forest station. This cavern consists of a series of clefts in the kenyte of the left bank of the Haugsbrung Valley at about 3470 meters. It is frequented by hyrax (*Procavia*) whose droppings

have apparently formed a small guano deposit (Jeannel and Racovitza, 1914).

MADAGASCAR AND THE MASCARENE ISLANDS

MADAGASCAR

One cave has been described (Jeannel and Racovitza, 1929) and a certain number of other sources of cave guano listed (Duclos, 1928).

GROTTE AUX PINTADES

In the northeastern part of the Ankoriko Peninsula between the Bay of Diego-Suarez and the Indian Ocean. The cave lies between Quaternary coral reef limestone and an underlying blue clay. It forms a gallery 400 meters long and 1 to 5 meters high, open at both ends. The upper entrance is 25 meters above sea level. Several holes exist in the roof of the cave. Heaps of guano were found near both entrances and within the cave about 50 meters from the lower entrance.

The following localities are listed by Duclos (1928) as producing "guano fanny," said to be the deposit of a large bat:

	TONS SUPPOSEDLY PRESENT
Nosi Banjoana	150
Nosi Ankarana	100
Mt. Ankonokono	60
Ampombimarivola	200
Tsarabanja	50
Bokoloso	40
Amboarana (Tuléar)	100

RÉUNION

A single but extremely interesting occurrence of phosphatization in a bat cave has been reported by Lacroix (1910, 1912, 1936).

TUNNEL DU CORMORAN, SAINT GILLES RAVINE

This ravine in the western part of the island contains a series of pools separated by cascades. The fourth pool on proceeding up the valley is known as the Bassin du Cormoran. The basalt of the sides of the valley is perforated by tunnels, and one of these tunnels below the Bassin du Cormoran is phosphatized. The cavern is 5 to 6 meters wide and in places reaches a height of 6 meters. It can be penetrated for a distance of 250

meters. The cave is described as being very humid.

Material from a cave labeled Bassin Bleu was sent to the Muséum d'Histoire Naturelle in Paris in 1822 by M. Desbassyns and was analyzed by Vauquelin (1822) who found it to contain alumina, ammonia, and phosphoric acid. A new analysis of this material by Pisani was published by Lacroix in 1910, and two years later the same author, having visited Réunion, gave an account of the occurrence of the mineral. It is just possible that the cave shown to Lacroix by the grandson of the original collector, 90 years after the first sample was collected, was higher up the valley, as the Bassin Bleu is the lowest pool in the Saint Gilles Ravine. Lacroix, however, seemed satisfied that he examined the original locality. The cave had formerly contained much bat guano, but this had mostly been removed. Such as was left was brown or blackish and pulverulent. The principal phosphate in the cave was identified as a variety of minervite, now known to be identical with taranakite. This occurred as a yellow, soft, sticky material in cracks in the basalt and under ledges of lava which occur along the lower part of the walls of the cave. Pieces of basalt that had fallen from the roof were found to be undergoing alteration to taranakite, and nodules of the mineral embedded in the guano certainly represented pieces of basalt that had been fully phosphatized. Analysis of the original material gave:

P ₂ O ₅	42.70%
Al ₂ O ₃	21.00
Fe ₂ O ₃	2.90
K ₂ O	1.20
(NH ₄) ₂ O	3.47
H ₂ O	29.80

This analysis differs from that of other specimens of taranakite in having a great part of the potassium replaced by ammonium. In a later work, Lacroix (1936) indicates that in partially phosphatized basalt from this occurrence, the olivine, plagioclase, and sometimes the glass of the original material can be replaced by a yellow colloidal-looking material, identified as redondite (i.e., probably barrandite), "dérivant de la minervite par perte de ses alcalis." The significance of the

last statement is presumably formal rather than genetic.

In addition to bat guano and taranakite, the cave yielded (Lacroix, 1912) other guano minerals. In the cavities of a vacuolated basalt in a part of the cave where the roof had collapsed, a crystalline mineral identified as newberyite, $\text{MgHPO}_4 \cdot 3\text{H}_2\text{O}$, occurred. The magnesium is suspected by Lacroix to be derived from the decomposition of peridote in the basalt. Certain concretions in the guano appeared to consist of a hydrated potassium ammonium sulphate, containing approximately:

K_2SO_4	45.7%
$(\text{NH}_4)_2\text{SO}_4$	28.1
H_2O	25

The material is considered (Lacroix, 1912, 1936) to be lecontite in which the sodium is replaced by potassium. Opal is known to occur in the cave, forming concentric layers on some of the stalactite-like projections of the basalt. This opal clearly represents silica derived from the decomposition of the basalt, but it is not certain that it is necessarily formed in phosphatization. Other tunnels in the same ravine have yielded other guano minerals; pulverulent brushite and struvite are recorded from undesignated localities, and the latter mineral specifically from a tunnel at Cap Bernard, near Saint-Denis (Lacroix, 1936).

EGYPT

Although the existence of bat guano from Egypt was known to Paris (1899) little analytical or other information is available. The one paper specifically discussing an Egyptian specimen relates to a very extraordinary occurrence. Popp reports a wax yellow, irregular, in part cavernose, stalactite-like accumulation of a markedly crystalline material from an Egyptian cave that proved on analysis to consist of:

Urea	77.80%
Creatin	2.55
Uric acid	1.25
Na_2HPO_4	13.45
H_2O at 100° C.	3.66
Insol.	0.575

This material, which represents an occurrence of urea as a crystalline mineral of biological

origin, was evidently formed by the rapid evaporation of bats' urine projected against the wall of a very dry cave.

PALEARCTIC NORTH AFRICA

A number of caves in Algeria and other parts of North Africa have produced guano. In general, the bats producing the deposits are probably identical with those occurring in the European bat caves, *Myotis myotis* (Borkhausen) and *Miniopterus schreibersii* (Kuhl) being the most important. The ecology of these bats is discussed in connection with the European bat caves. The first record of North African bat guano appears to be that of Mangon (1857) who indicates that deposits were known in Algeria. Little has been written about individual occurrences. Jeannel and Racovitza, who have listed a number of caves in Algeria explored biologically, noted (1908) guano deposits in four out of 18 caves that they had themselves examined. In later lists, other caves studied by other workers were enumerated, but it is improbable that the notes on these are exactly comparable with those on the earlier series.

Two caves, the Grotte du Veau Marin, Chenoua-plage, Tipaza, at sea level, and the Ifri Ivenan, 2 kilometers west of Oulad ben Dahmane, Palestro, are recorded as being exploited as guano caves. In the cave El Ghar, Oued Berdi, Aïn Bessem, about 50 cm. of dry guano of a sandy texture are recorded as produced by social bats. Solitary *Rhinolophus* also inhabited the cave. A small amount of guano is noted in the Ifri-bou-Tigherset, Beni Mendes, Dra-el Mizan, at an altitude of 1200 meters, the highest record for bat guano in North Africa, though pigeon¹ guano was encountered at 1550 meters in the Azerou bou Adhfel, Aït-Zikki, Haut Sebaou (Jeannel and Racovitza, 1918). The Grotte de Beni-Add, Aïn-Fezza, Tlemcen, in Oran, had bat guano in the inner end, 200 meters from the entrance, and that of pigeons in the vestibule (Jeannel and Racovitza, 1929).

¹ The pigeon or dove guano found in caves in parts of the Palearctic region is presumably to be attributed to the geographically appropriate subspecies of *Columba livia* Linnaeus.

A peculiar case is provided by the Grotte du Lac Souterrain, Hamman Meskoutine, Clauzel, Constantine, where a deposit had apparently formed on an island in an underground lake. The largely artificial cave providing the outlet of the fourth spring of the Ravin de Misserghin also contained bats and guano.

TOUR COMBES, MISSERGHIN

On the road to Tlemcen, 10.4 kilometers from Oran, a cave exploited for phosphate was examined by Pallary and Fabriès (Carnot, 1895a, 1895b). The cave is in Tertiary limestone, with a stalagmite floor covered with red brown cave earth, 1 to 3 meters thick, in which veins and masses of white spongy material, marked with yellow, red, or black, were exploited as a source of phosphate. The cave contained no guano or bones, and Carnot believed that the phosphate was brought into the cave by circulating water enriched with the products of organic decomposition. Since, as has just been indicated, guano deposits occur in the

region, there seems no reason to doubt that the Tour Combes phosphate was not derived from such a source. The origin of the alumina and silica present is less clear. The white material contained:

H ₂ O -100° C.	13.40%
H ₂ O 100°-180° C.	10.55
H ₂ O +180° C.	4.35
Al ₂ O ₃	18.18
K ₂ O	5.80
(NH ₄) ₂ O	0.48
CaO	0.31
P ₂ O ₅	35.17
SiO ₂	11.60

Other samples contained up to 0.91% (NH₄)₂O, and in some there was a very large quantity of silica, up to 84%. The reddish material contained iron; the black is said to have been colored by manganese oxide and a small amount of cobalt. The typical white material, though not even microscopically crystalline, was identified by Carnot as minervite and would now be referred to taranakite. His analysis is further discussed below.

CAVE GUANO IN EUROPE

Cave guano primarily derived from bats is abundant in certain caves in Europe. Though a considerable part of these deposits is of recent origin, the largest accumulations appear to date from the Pleistocene. In most cases the old fossil deposits are found to contain the bones of cave bears and apparently date from the Riss-Würm interglacial. A certain number of older chiropterite deposits are, however, known. It is not always possible from the available accounts to ascertain whether a given deposit is recent or fossil, and whether in the fossil deposits worked for phosphate the material exploited was truly excretory or was composed primarily of fossil bones. The localities therefore have been arranged on a purely geographical basis, though from a scientific point of view a temporal as well as a spatial classification would have been preferable if it could have been achieved.

If only the numbers of localities in which they have been recorded is considered, as, for instance, in Wolf (1934-1935), there can be little doubt that the commonest European cave bats are the horseshoe bats of the genus

Rhinolophus, *R. ferrum-equinum* being the most abundant species. The horseshoe bats are, however, not social and do not aggregate to form large clusters of sleeping individuals. They seem indeed rarely to tolerate mutual contact. They are moreover primarily cavernicolous in winter, so that their entire ecology and behavior are not conducive to the production of guano deposits (Jeannel, 1926).

A good many vespertilionid bats habitually hibernate in caves. Barrett-Hamilton (1911) indicates among the British species that this habit is known in *Plecotus auritus* (Linnaeus), in *Myotis daubentoni* (Kuhl), *M. mystacinus* (Kuhl), and in *M. nattereri* (Kuhl). The last-named species is apparently markedly social. As in the case of the bats hibernating in caves in the northern United States, it is unlikely that any significant guano deposits are produced by these species.

Myotis myotis is by far the most important guano bat in Europe. The species is distributed northward into southern Sweden, throughout Germany, the Netherlands,

France, the Iberian Peninsula, and Italy, southward into Tunis, and eastward through Hungary and Rumania into western Asia. It is conspicuously absent from the British fauna, although a few casual specimens taken in England suggest that stragglers may cross the English Channel, though they are unable to establish themselves. *M. myotis* is a markedly migratory species. In Brandenburg, Germany, Eisentraut (1936) found that bats that had aggregated in winter dispersed in general northward and eastward. Social groups of females are established in localities far from the winter retreats, and in these social groups the young are born and nursed. Though Eisentraut's observations relate mainly to aggregates found in buildings, there can be little doubt that the same sort of behavior is exhibited by cave-living populations. Casteret (1939) observed a colony of about 400 *M. myotis* in the Grotte des Tignahustes, Aventignan, Hautes Pyrénées. The bats began to arrive at the end of March and occupied the cave until the end of August and beginning of September. All the specimens examined were females, and Casteret states that he has never found a male in a Pyrenean cave. He indicates that of about 500 Pyrenean caves examined, only about 10 contained colonies of the species. The species has been identified from skeletal remains of dead specimens in caves at altitudes as high as 2200 meters.

It is evident that in the Pyrenees, such guano deposits as are produced by *M. myotis* are likely to be the results of the activities of breeding females in summer. It is, however, apparent that in other parts of Europe, guano may be deposited by colonies of the species that occupy caves in the winter. The Teufelslochhöhle near Budapest in Hungary, discussed below, in which thousands of bats winter, and from which *M. myotis* and *Rhinolophus hipposideros* are recorded, provides an example of such a locality. In southern France, Jeannel (1926) regards *Myotis oxygnathus* (Monticelli) and *Miniopterus schreibersii* as significant producers of guano, though they are evidently less important than is *M. myotis*. Both are meridional species; *Miniopterus schreibersii* occurs in Spain, southern France, Switzerland, Italy, the Balkans, Hungary, and southward into

Morocco, Tunis, and Algeria, where it may occur in great numbers (Laurent, 1937). Jeannel points out that it does not form such dense aggregates as does *M. myotis*, with which it is often associated, because it hangs from the roof of its retreat by all four limbs and so occupies more space than do the vespertilionid bats. Casteret makes the curious observation that *Miniopterus* leaves the Grotte des Tignahustes at the height of summer, when *M. myotis* is giving birth to young, but later in August some individuals return to the cave. *Myotis oxygnathus*, if a valid species, is very close to *M. myotis* and occurs with the latter in the southern part of its range. It is smaller, rarer, and probably therefore less important as a producer of guano. There has, however, been continual doubt as to the true taxonomic status of *M. oxygnathus*; some authors, including Gulino and Dal Piaz (1939), the most recent students of the European bat fauna, consider it a subspecies, though admitting its occurrence with *myotis*. It is improbable that the existence or status of *oxygnathus* is of any great importance from the standpoint of the present work.

It is interesting to note that the European representative of the free-tailed bats, *Nyctinomus teniotis* (Rafinesque), though common throughout the Iberian Peninsula, is apparently ecclesiophilous rather than cavernicolous and is not recorded as producing guano.

When the deposits of fossil bat guano or chiropterite are considered, some evidence becomes available that in the Pleistocene other social bats inhabited Europe. The largest late Pleistocene deposit, that of the Drachenhöhle near Mixnitz in Austria, contained remains of three bats that were evidently once common in the cave, namely, *Barbastella schadleri* O. Wettst, *Plecotus abeli* O. Wettst, and *Eptesicus nilssonii* (Keyserling and Blasius). The first two species are extinct; their modern congeners are not markedly social. The third, a somewhat boreal form which still inhabits the cave, is not recorded elsewhere as producing significant guano deposits. It is evident from the extent of the deposit that during the last Interglacial the Drachenhöhle contained a large population of bats, and it is not unlikely that this population consisted chiefly of the two common extinct species. In the

earlier Pleistocene or late Pliocene chiropterite deposits, such as that of Gundersheim, a number of other species occurs. The most remarkable of such deposits is probably that of Beduer, in the Département du Lot, France, where a bat described as *Vespertilio oltinus* occurred in great quantity. As is indicated below, this bat requires further study before its affinities become clear, but it is probably

mer may be quite low (11° C.) by epigeal standards. Throughout Europe, wherever a reasonably large series of caves at different altitudes exists, the bat and guano caves tend to be rarer at higher than at lower altitudes (fig. 89). This is probably largely a function of temperature. Jeannel and Racovitza indicate that in general the drier caves or parts of caves are preferred by bats. A very con-

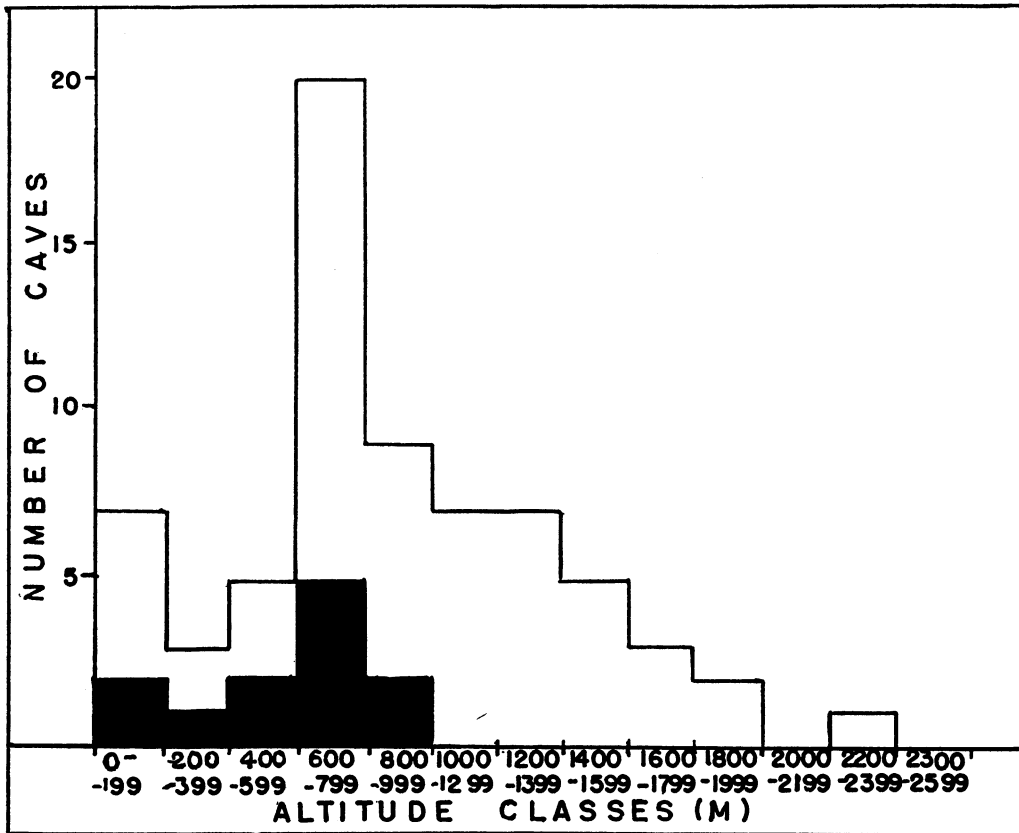


FIG. 89. Histogram showing altitudinal distribution of all (open) caves, and those with guano (black) in the Spanish Pyrenees.

very different from any modern European species that produces guano.

Not all caves are suitable habitats for bats; it is indeed probable that the supply of guano in any region depends primarily on the suitability of its caves. It is possible to gain some idea of the requirements from the accounts of Jeannel and Racovitza. The coldest caves are evidently generally avoided, though the temperatures within caves inhabited in sum-

merable air current is, however, unfavorable (Jeannel and Racovitza, 1929, p. 546). Two of the Yugoslavian caves that they examined (figs. 91, 92) are instructive in indicating how the form of a cave, in one case the two entrances at different levels, in another the general slight upward slope, apparently determines the optimum ventilation and so the optimum humidity. The form and texture of the roof of the cave are no doubt significant

ecological factors. Frequently the bat colonies are found near the entrance or in the middle of the cavern, but in many cases the bats congregate at the far ends of the passages that they inhabit, sometimes at extraordinary distances from the entrance. There is at times but not invariably a separation of *Myotis myotis* and *Miniopterus schreibersii* into quite separate colonies when they inhabit the same cave. The existence of old masses of guano in one region of a cave and fresh guano under a flourishing colony in another part indicates that the bats do not occupy the same regions perennially.

YUGOSLAVIA

Jeannel and Racovitza (1929) describe 24 caves in Yugoslavia, of which seven have guano deposits. Three of these caves evidently contained very considerable bat colonies.

LAZAREVA PEĆINA, ZLOT, BOLJEVAC, TIMOK

A large cave, at an altitude of 350 meters, in Mesozoic limestone dividing into two galleries near the entrance. The right-hand gallery turns sharply about 60 meters from its origin and finally leads to a passage at the end of which a bat colony is found, about 400 meters from the entrance (fig. 90). The floor of the cave was covered with several meters of guano.

POPŠIČKA PEŠTER, SVRLJIG, TIMOK

A fairly long, narrow cave, at an altitude of 600 meters, with a double entrance (fig. 91). The disposition of the entrances leads to an air current which tends to keep the cave relatively dry and warm (11.7° C., June 12, 1923) though probably very variable. Jeannel and Racovitza comment on these climatic factors as making the cave unsuitable

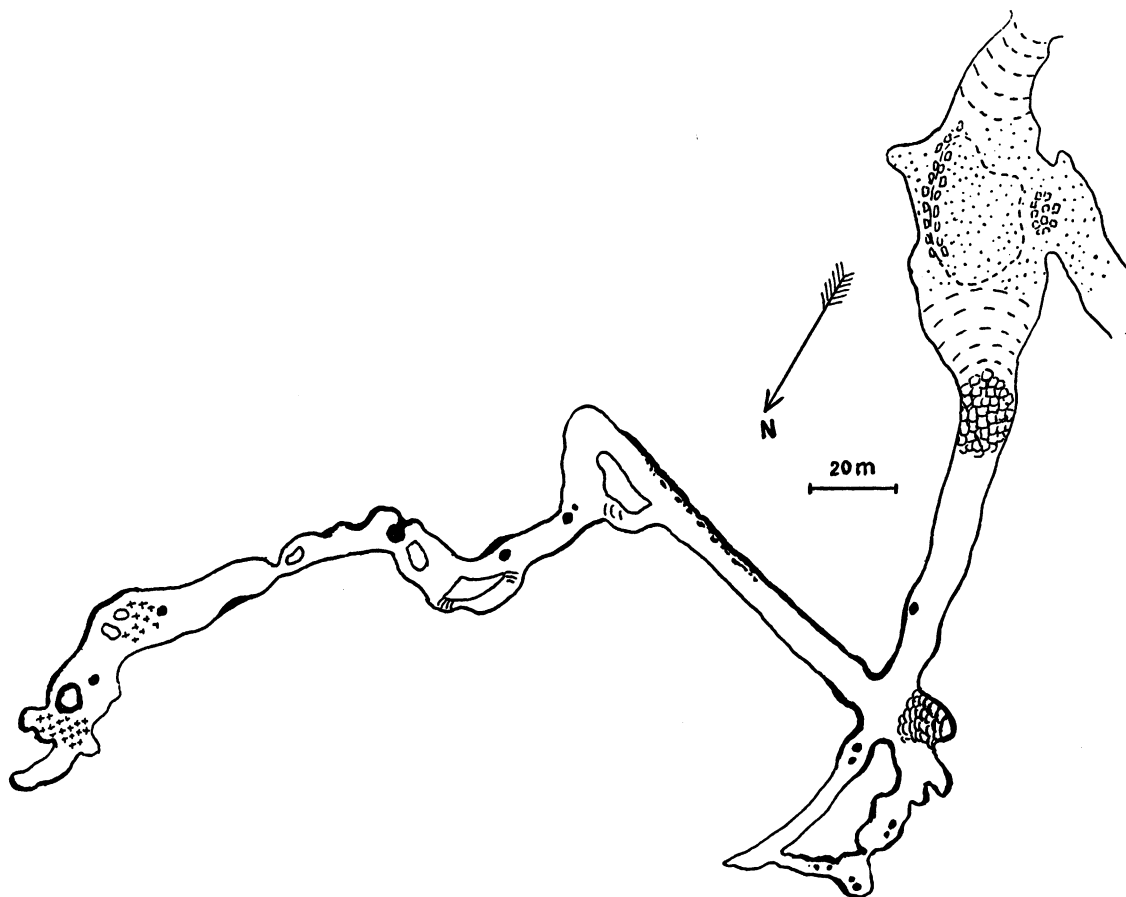


FIG. 90. Plan of Lazareva pećina. After Jeannel and Racovitza.

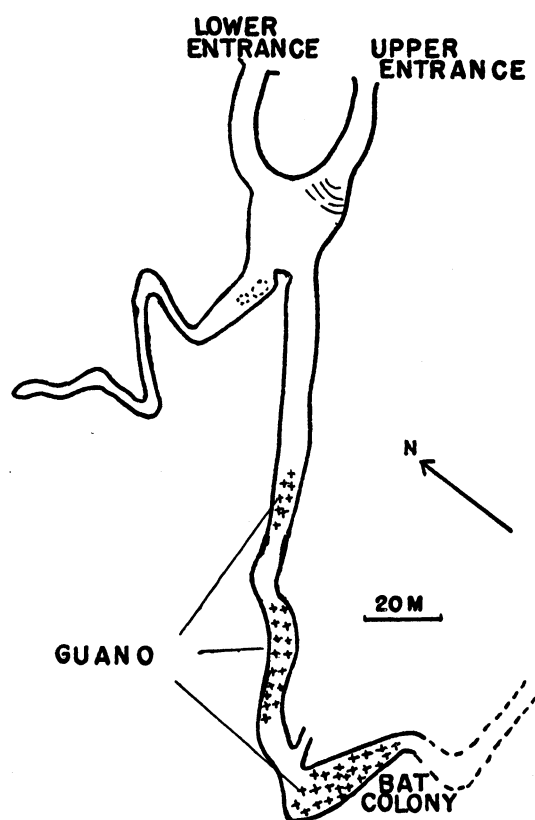


FIG. 91. Plan of Popšička pešter. After Jeannel and Racovitza.

for a true troglobiont fauna but suitable for bats. The main bat colony was, however, living in the dampest part of the cave, though dry guano nearer the entrance indicated that the bats were not restricted to the region where they were observed. The total amount of guano was evidently considerable.

**HADJI PRODANOVA PEĆINA, RAŠČICI,
ŠUME, MORAVICA, ČAČAK**

A narrow straight cave (fig. 92), at an altitude of 650 meters, in Cretaceous limestone. It has a terminal hall in which a large bat colony, living about 150 meters from the entrance, has produced a considerable mass of guano. The cave is dry and warm (11.7° C.), having a slight upward slope throughout and in consequence a descending air current along its floor, presumably compensated by a warmer draft along the ceiling.

Moser (1878) gives for unspecified Balkan cave guanos:

H ₂ O	8.69%	15.04%
N	5.47	3.38
P ₂ O ₅	4.84	7.90

RUMANIA

Jeannel and Racovitza (1929) examined or obtained data from 97 caves, mainly in Transylvania. Of these, 12 are noted as having some sort of bat guano other than scattered droppings. Of the 71 caves situated at altitudes below 1000 meters, 11, or 15.5%, had some deposits, while of the 26 caves lying above 1000 meters, only the Ghetarul dela Barsa, Pelroasa, Vașcău, Bihor, at 1140 meters, had a few bats and a little guano, although the temperature on August 26, 1921, was only 4° C. in the cave. Evidence was obtained in the Peșterea dela Măgura,

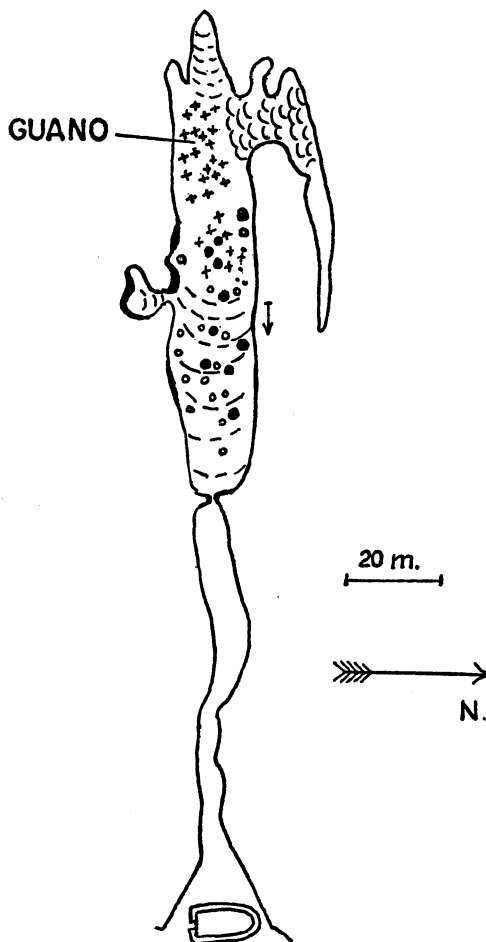


FIG. 92. Plan of Hadji Prodanova pećina. After Jeannel and Racovitza.

Vaşcău, Bihor, of two social species, almost certainly from the account *M. myotis* and *Miniopterus schreibersii*, occupying part of different galleries and being absent in June but present in August. The dates are inconclusive, but Jeannel and Racovitza thought other solitary species used the cave in the winter. The most remarkable occurrence that they report relates to the Peșterea dela Ferice, Beiuș, Bihor, in which groups of bats occupy shallow cavities in the roof. The droppings collect below, but the urine apparently is largely directed against the walls of the cavities and has produced a dark substance by interaction with the limestone. None of the deposits that are described appear to be of any great size. The largest was a heap 2 meters high in the Peșterea dela Cheia Ampoiții, Ighiu, Alba.

Moser (1878) gives the following analyses from caves now in Rumania:

	TRAN- SYLVANIA	ORADIA MARE (GROSSWARDEIN)		
H ₂ O	13.68%	40.28%	39.60%	34.97%
N	2.84	4.84	5.20	4.88
P ₂ O ₅	5.06	0.76	1.80	3.21

In contrast to the small recent deposits of this region, one cave has provided evidence of immense late Pleistocene deposits of bat guano, now decomposed to chiropterite.

CSOKLOVINA CAVE

A cave in the Lunkany Valley, near Petrosam (Petrosény) in the Transylvanian Alps, now within the boundary of Rumania, though formerly in Hungary. The cave was examined several times on account of its phosphatic deposits. Götzinger (1919) has summarized the previous information in his account of his own explorations.

The cave is about 450 meters long; the outer half is dilated to form three major halls, about 25 meters wide, and the inner half is an almost straight passage rather over 5 meters wide. The cave is of late Tertiary origin, and the floor in its unexcavated condition was covered in part with rock debris, particularly near the outer end, and in part with phosphatic earth. Stalactites, stalagmites, and sinter deposits had formed locally. Part of the cave earth deposit exhibited polyg-

onal cracks at the surface, which cracks descended to a depth of 2 meters in the innermost part of the cave. In places the surface layer of cave earth consisted of black or chocolate-covered, loose, fresh bat guano formed by colonies of bats. Jeannel and Racovitza (1929) indicate, however, that bats no longer inhabit the cave. Götzinger gives a number of profiles through the cave earth. The maximum depth of the deposit appears to have been 20 meters. Unfortunately analyses were made only on an arbitrary group of samples which are not systematically arranged. The various strata were compared visually with these samples, but the comparison is unlikely to give any valid chemical information. In the middle part of the cave, a profile through the Great Hall shows bone-bearing earth alternating with guano. The stratigraphy is clearly contingent on the thickness of the profile, and the higher parts of the original floor bear less deposit. The most complete profile appears to indicate three beds of bone earth, but one profile (20) consisted almost entirely of gray or brownish gray chiropterite 10 meters deep, without bones. In the long passage forming the inner half of the cave, a profile 10 meters deep again shows gray guano at the top, some bone earth at 2 meters, gray guano down to 5 meters, and bone earth with rounded quartz pebbles in the bottom 4 meters. At the inner end of the cave, the deposit consisted of a grayish guano down to 10 meters with bones at 1.5 meters. Below this there was gray and brown guano with quartz pebbles down to the bottom of the deposit at 15 meters. The bones are evidently almost exclusively those of the cave bear, *Ursus spelaeus*. Inasmuch as considerable thicknesses of phosphatic earth without bones occur in most of the profiles, it is probable that most of the so-called guano is leached bat guano or chiropterite and not derived from the excreta or decomposing bodies of cave bears. This matter can be considered quantitatively in the case of certain of the Austrian caves discussed below.

Archaeological material referable to the Mousterian and Aurignacian has been recovered from the cave.

The area of the parts of the cave bearing

phosphate was about 4000 m², and the volume of the whole deposit was estimated as about 50,000 m³. The sample richest in phosphate was a sample from the surface of the deposit in the main hall. This contained 29.74% total P₂O₅ and 22.44% citric-acid-soluble P₂O₅. The fraction soluble in citric acid varied greatly, from 3.5% in the sample poorest in total P₂O₅, containing only 3.46%, from a depth of 2.5 meters, to 98.3% in a sample containing 17.51% P₂O₅ from a depth of 7 meters. The mean total P₂O₅ was 15.2%, of citric-acid-soluble P₂O₅, 9.4%.

The high citric-acid-soluble fraction is presumably to be associated with the occurrence of brushite in the cave. Schadler (1932) records this mineral as common not merely in the superficial layers of the chiropterite where evaporation is taking place, but also in cracks between fallen limestone blocks deep in the deposit. Gypsum occurs in a similar manner. The two minerals occur in discrete masses, but ardealite, a very remarkable double salt, CaHPO₄·CaSO₄·4H₂O, also occurred as a white or yellowish powder in the drier, acid chiropterite. Ardealite is not a mechanical mixture of gypsum and brushite, its X-ray diffraction pattern being characteristic. Analyses gave:

	SCHADLER	HILL AND HENDRICKS, 1936
H ₂ O -110° C.	0.62%	—
H ₂ O +110° C.	24.99	—
CaO	36.42	32.13%
SO ₃	21.11	23.08
P ₂ O ₅	21.71	23.53
Insoluble	0.39	—

HUNGARY

TEUFELSLOCHHÖHLE, BUDAPEST

Rózsa records the presence of considerable amounts of bat guano in this long, narrow, rather complex passage-cavern, in which thousands of bats are said to congregate during the winter. Both *Rhinolophus ferrum-equinum* and *Myotis myotis* are recorded (Dudich, 1925) from the cave; the latter species is presumably the important guano producer.

The guano is described as forming brown earthy masses, only the upper layers smelling

of ammonia. It occupied localized areas of the floor of the cave, varying in thickness from a few centimeters to several meters. The total mass was believed to be of the order of 150 tons. The nitrogen content varied from 0.54% to 10.26%, the mean being 6.07%. The P₂O₅ content varied from 2.40% to 7.33%, the mean being 3.00%. These analytical data are based on material dried at 100° C.; *in situ* the water content varied very greatly. Another cave in the same region, in Mt. Nagyszal, near Weitzen, contained about 35 tons of guano. The nitrogen content varied from 1.06% to 4.04%, the mean being 2.40%. The phosphate content varied from 2.77% to 6.68%, the mean being 4.87%.

PRSZNICZE (PRIESNITZ) CAVE

In the Dachstein limestone of a mountain between Labatlan and Turdos, near Gran, inhabited by a large bat colony and containing a deposit of guano about 2 meters thick (Tietze, 1872). The guano consisted of a plastic, chocolate-colored material, in which individual fecal masses could be recognized. Analysis (I) of this material indicates a relatively undecomposed guano, but Scheibler (1872) gave another analysis (II) of a much more phosphatic material, apparently from the same locality:

	I	II
H ₂ O at 100° C.	31%}	48.00%
Ignitable	61.5}	
N	—	1.88
P ₂ O ₅	1.392	11.54

A series of analyses by Moser (1878) from a locality designated as Grau, but probably a misprint for Gran, may well be based on guano from the same cave:

H ₂ O	N	P ₂ O ₅
13.94%	8.39%	4.65%
35.82	1.40	8.99
62.65	5.15	1.56
40.64	2.88	6.85
71.18	2.88	1.98
10.50	4.60	7.44
15.59	3.88	19.13

GYOR (RAAB)

West of the localities just considered, apparently the site of bat caves. Schwarz (1879) analyzed guano from these caves and found:

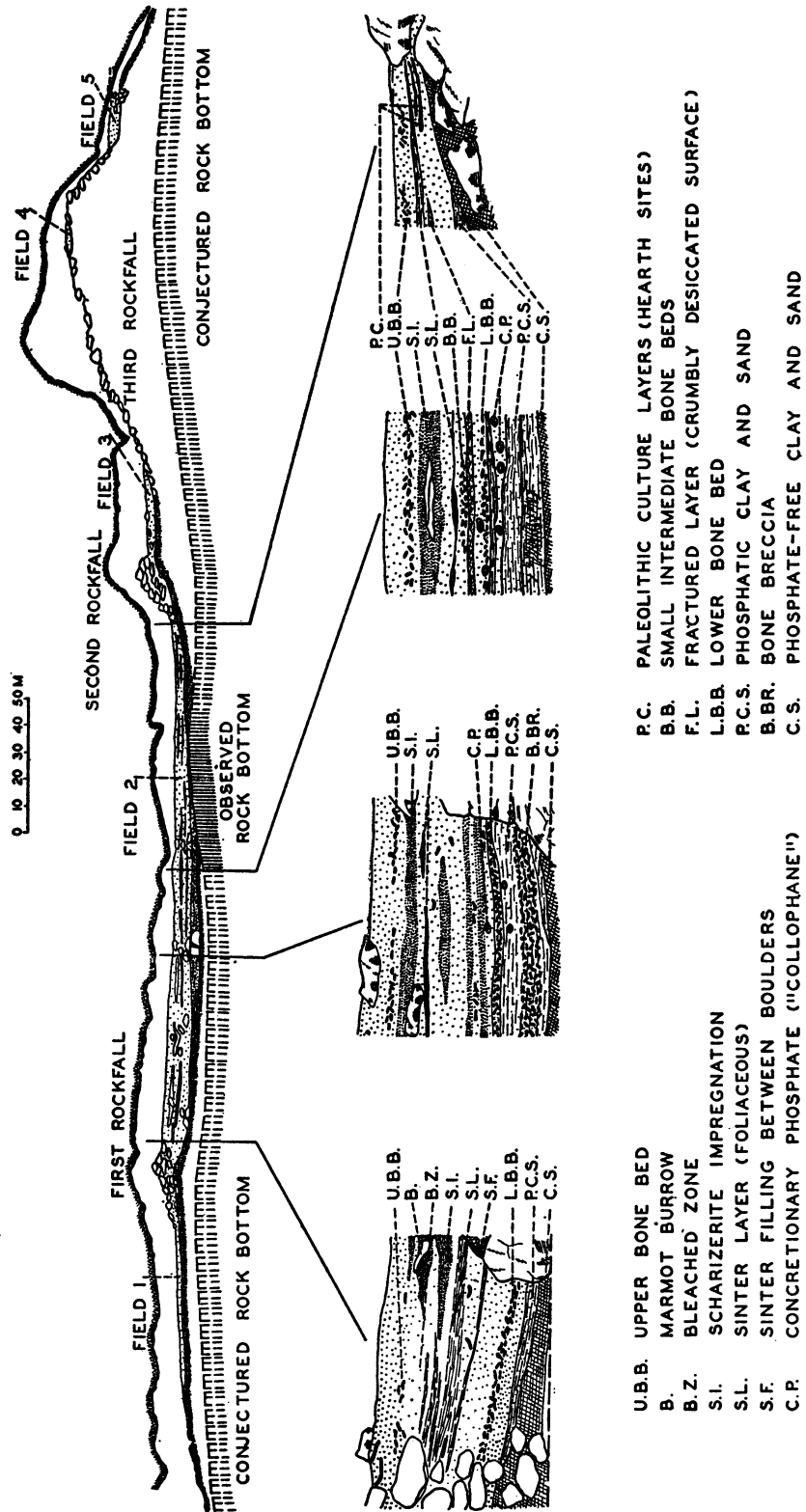


Fig. 93. Section through the Drachenhöhle. After Schadler.

Volatile	31.62%
N	0.70-0.98
P ₂ O ₅	10.56-11.03
Sand	32.80

Part of the phosphate is said to have been present as (Al,Fe)PO₄.

OTHER HUNGARIAN LOCALITIES

Fruwirth (1883) records a deposit in the Dombicza Cave; the position of this locality, which may well now not be within the political boundary of Hungary, has not been ascertained.

Tod (1859) gives the following analysis of a sample from an unspecified Hungarian cave:

H ₂ O	13.30%
Nitrogenous organic matter	53.89
Carbonaceous and humic matter	12.20
Organic N	3.20
N·NH ₃	4.39
N·NO ₃	0.19
Na ₂ O	1.76
K ₂ O	
CaO	
MgO	
Fe ₂ O ₃	0.38
P ₂ O ₅	3.15
SO ₃	1.83
Cl	0.45
SiO ₂ and sand	3.13

AUSTRIA

The best-studied phosphate deposit in any cave is that formerly filling a large part of the Drachenhöhle, near Mixnitz, north of Graz; this and certain other Styrian caves will therefore first be considered.

DRACHENHÖHLE, MIXNITZ

The Drachenhöhle is a relatively simple cavern in Middle Devonian (Upper Lantsch) limestone. It was formed by fluvial solution during the Miocene. Three large rock falls which tend to divide the cavern into chambers are attributed by Göttinger (1931) to tectonic disturbances during the late Miocene and Pliocene.

The cave is about 560 meters long and consists of an entrance chamber about 125 meters long, ending at the second rockfall, and a rather irregular terminal portion in part interrupted by the third rockfall (fig. 93).

The main deposits of the floor of the cavern are the blocks of limestone of the rockfalls and phosphatic cave earth. The latter substance formed the floor of the first and second chambers, and smaller deposits behind the second rockfall and in the terminal part of the cavern. The volumes of phosphatic earth present in these different parts of the cave were:

Field 1, from entrance to first rockfall	450 m ³
Field 2, from first to second rockfall	16,500 m ³
Field 3, above second rockfall	2,000 m ³
Field 4, on third rockfall	250 m ³
Field 5, behind third rockfall	1,500 m ³

The total quantity of phosphatic material in the cave appears to have been 24,000 tons, equivalent to about 3000 tons of P₂O₅. The second field, between the first and second rockfalls, is the most significant not only in quantity but in its development of stratigraphic detail.

The stratigraphy of field 2 will therefore first be described. The basal material is clay, sand, or gravel of fluvial origin and free from, or poor in, phosphate. This is overlain by sand and clay, which is somewhat phosphatic and which contains in places fluvial quartz, pebbles, and broken dripstone. Such coarsely crystalline red dripstone and calcareous sinter were apparently formed in the cave before phosphatization began. In one place a bone breccia is intercalated in this layer. The partially phosphatized clay and sand are covered with a thick layer of phosphatic earth or chiropterite in which are intercalated two major and at least one minor bone beds. Between them a crumbly layer apparently represented an old cracked surface, and above it, but below the upper bone bed, there was a layer containing foliaceous sinter.

The general sequence of these deposits is illustrated in the four sections given in figure 93.

The small phosphate fields (3, 4, and 5) in the depths of the cave are much less deep than field 2, but a basal bone bed is developed in field 5. The deposit of the outer part of the cave (field 1) also has a basal bone bed in its inner portion. This field is of considerable interest because the distribution of

TABLE 46

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	%	%	%	%	%	%	%	%	%	%	%	%
SiO ₂	0.31	40.09	34.56	53.87	21.93	26.84	37.84	74.02	15.68	22.52 (21.47)	17.75 (16.67)	21.93 (20.87)
TiO ₂	0.02	1.29	1.02	1.43	0.24	0.69	0.69	0.80	0.52	0.40 (0.32)	0.37 (0.29)	0.24 (0.18)
Al ₂ O ₃	0.06	23.57	26.28	13.37	5.78	1.96	10.94	12.51	17.90	5.86 (2.89)	5.40 (3.79)	5.78 (3.45)
Fe ₂ O ₃	0.22	12.40	12.99	10.34	2.39	4.93	5.66	3.40	4.32	3.26 (0.54)	2.63 (0.41)	2.39 (0.26)
MnO	—	0.10	—	0.12	0.08	tr.	0.11	—	tr.	0.07 (tr.)	0.08 (tr.)	0.08 (tr.)
CaO	55.52	3.89	5.80	1.41	28.22	32.12	19.62	1.78	1.80	31.20 (0.09)	26.26 (0.14)	28.22 (28.05)
MgO	0.09	1.78	1.12	1.81	0.59	0.30	0.17	0.42	0.82	0.66 (0.25)	0.28 (0.23)	0.59 (0.21)
K ₂ O	0.085	4.30	3.25	3.78	1.40	—	—	—	—	1.38	1.14	1.40
Na ₂ O	0.024	0.63	0.42	0.91	0.36	0.35	—	—	—	0.41	0.28	0.36
P ₂ O ₅	0.005	0.10	0.70	5.34	22.63	25.02	17.40	3.99	24.50	25.10 (0.02)	18.54	22.63 (tr.)
CO ₂	43.72	2.82	3.66	0.80	2.81	2.01	0.89	0.35	—	2.87	2.76	2.81
S	—	—	—	—	0.23	—	—	—	—	0.33	0.34	0.23
C	—	—	—	—	—	—	—	—	—	0.67	10.93	4.99
N	—	—	—	—	0.69	—	—	—	—	0.15	3.42	0.69
H ₂ O <100° C.	0.25	—	—	1.15	—	—	—	—	—	dried at 110° C.	—	—
H ₂ O 100°–200° C.	—	—	—	—	—	2.55	2.98	1.74	20.33	4.38	7.41	5.12
H ₂ O >200° C.	—	8.75	10.15	5.37	5.12	3.47	3.46	1.15	13.20	—	—	—

I. Limestone of cave wall, gray with red veins; K₂O and Na₂O insoluble in dilute acid, determined on a separate sample. Machatschki, 1931.

II. Clay from large field 4. Machatschki, 1931.

III. Clay from descent, field 5. Machatschki, 1931.

IV. Basal clay of phosphate deposit. Machatschki, 1931.

V. Phosphate, 0–3 meters, field 1, zone 10.

VI. Phosphatic earth, brown, containing quartz particles, 5 meters, field 2, zone 18. Machatschki, 1931.

VII. Phosphatic earth, brown, clayey, 5 meters,

field 2, zone 23. Machatschki, 1931.

VIII. Phosphatized quartz sand, 7 meters, field 2, zone 23. Machatschki, 1931.

IX. Light phosphatic veins in gray clay layer, 7.5 meters, field 2, zone 23. Machatschki, 1931.

X. Yellow brown nodule in black brown layer, field 1, zone 10, 0–3 meters. Figures in parentheses acid insoluble where separately determined. Marchet, 1931.

XI. Black brown layer impregnated with scharizerite, enclosing material of previous analyses. Marchet, 1931.

XII. Normal red brown material.

limestone fragments fallen from its roof clearly shows an increase in such material towards the upper part of the deposit, which indicates increase in frost action, and also because a neolithic hearth was discovered at the outermost edge of the cave earth. This hearth was covered by phosphatic earth, some of which must therefore have formed in post-glacial times.

Schadler (1931) and the other investigators of the site conclude that the main deposit of field 2 was formed in the Riss-Würm interglacial. A paleolithic hearth and two closely superimposed culture layers were found in the most remote part of field 2. These lie below the foliaceous sinter layer, and the lower one lies immediately over a layer of flat limestone plates. The culture layers are in part equivalent stratigraphically to the crumbly cracked layer. The artifacts obtained are referred by Kyrle (1931) to a Mixnitz stage in the Alpine paleolithic equivalent to the Acheulean.

The principal inhabitants of the cave during the period of phosphate deposition appear to have been cave bears (*Ursus spelaeus*). It is therefore natural to inquire whether the phosphate could possibly have been derived from the bodies and excreta of these animals. Approximately 260,000 kilograms of cave bear bones occurred in the cave. The skeletal material accounts for 78,000 kilograms of P_2O_5 and apparently corresponds to about 9000 to 12,000 individuals. When the possible role of bears in producing the phosphatic earth is considered, it is obviously necessary to allow for the phosphate of their soft parts and for the phosphorus excreted by them in the cave. The excreta were probably mainly lost outside the cave. Schadler quotes Abel as believing that the total population of bears may have been as great as 30,000 to 50,000 throughout the entire period of occupancy of the cave, but in addition to the skeletal material recovered it is very improbable that more than 200,000 to 350,000 tons of phosphorus could have been derived from these animals. This leaves about 2,500,000 kilograms to be accounted for. The only reasonable source of this phosphate would appear to be bat guano. The production of the phosphatic earth from bat guano containing 0.5% to 1.5% P_2O_5 and 0.1% to

0.2% CaO would require the solution of about 10,000,000 tons of limestone. Since it is estimated that the total amount of water dripping into the cave is annually of the order of 700,000 liters and that this contains the equivalent of about 1270 kilograms of $CaCO_3$, it would take only 8000 years to supply the requisite calcium. Schadler considers that 1 cubic meter of bat guano contains from 5 to 8 kilograms of P_2O_5 , while an equal volume of the phosphatic earth contains 100 to 150 kilograms. The guano necessary to form the earth would therefore have had a volume of at least 12 times that of the existing deposit. The cave in the region of field 2 is inadequate to accommodate such a volume. Part of the guano may have been deposited in the upper part of the cave and have been carried into the region of field 2 by water, but the stratigraphy indicates that, in general, decomposition and compaction occurred gradually as diagenetic processes. This is in accord with what certainly has happened in many other bat caves.

A narrow stratum of limited horizontal extent, in the middle of the chiropterite, yielded numerous bones of small mammals (Wettstein-Westerschheim, 1931). The deposit probably owes its existence to the pellets regurgitated by an owl, though it is not certain that the material has not been redeposited by water since regurgitation took place. By far the greater number of individual bones are chiropteran, at least 111 individual bats being represented. The remains of at least 19 specimens of the long-tailed field mouse *Apodemus sylvaticus* and of at least five specimens of other mammalian species were also present. As has been indicated above, the commonest bats were two extinct species, *Plecotus abeli* (37 or more individuals) and *Barbastella schadleri* (39 or more individuals). The former species was smaller than the modern long-eared bat, *P. auritus*, and differed in details of its dentition; the latter species was larger than the modern barbastelle, *B. barbastella*, and had more robust dentition. The differences between these bats and their existing European congeners are probably great enough to suggest that they might have differed from them somewhat in habits. The third most abundant bat, represented by at least 25 individuals, was *Eptesicus nilssonii*,

which still occurs in the cave though not in numbers. Four species of *Myotis*, the extinct *M. mixnitzensis* O. Wettstein, and the living *M. mystacinus*, *M. nattereri*, and *M. bechsteinii*, were present as fossils but were rare.

Modern bat bones indicated that nine species have lived in the cave in recent times. Of these only *Eptesicus nilssonii* and *M. mystacinus* are common to the fossil and recent collections, and they are represented by single individuals in the latter assemblage. *M. myotis*, which does not occur in the fossil collection, is the only species that is common in the recent collection. It is represented by

mm. in diameter. The irregular variation in size distribution is in part due to local redistribution by water in the cave.

The more complete analyses of the chiropterite and some of the associated deposits are set out in table 46. Schadler gives in addition analyses (table 47) for the more superficial parts of the deposit of field 2 based on material dried at 110° C.

It will be observed that the published analyses are rather unsystematically arranged, but Schadler has summarized the results of a large number of other analyses. The mean P_2O_5 content is 13.4% of the wet

TABLE 47

	I	II	III	IV	V
SiO ₂ and insol.	35.77%	31.99%	27.66%	32.76%	34.10%
Al ₂ O ₃	1.12	0.23	1.35	0.63	2.42
Fe ₂ O ₃	3.04	3.74	2.66	3.69	6.02
CaO	30.53	36.00	36.83	30.40	41.71
P ₂ O ₅	18.88	22.34	18.56	21.43	22.00

I, II. 0.5 meter, middle.
III-V. 1.5 meters, north wall.

at least 23 out of 35 individual bats recovered from modern deposits; no other species is represented by more than three individuals. It is reasonable to conclude that, since the fossil collection comprises no species of recent bat known to form large social aggregates which produce guano, the major part of the deposit was the work of the two common extinct species, *P. abeli* and *B. schadleri*. It must, however, be remembered that the collection of bat bones probably reflects the fauna of a very limited time span and that considerable changes may have taken place during the climatically variable period when the deposit of chiropterite was forming.

The main phosphatic constituent of the chiropterite appears microscopically as a yellow brown to blackish brown isotropic material of refractive index about 1.6. It is supposed to be a colloidal calcium phosphate. Mechanical analysis indicates a considerable diversity in the size distribution in different parts of the deposit. From 5.70% to 84.50% of the material fell in the 0.02- to 0.002-mm. range and from 7.53% to 49.84% in the 0.02- to 0.2-mm. range. In all samples at least 36.41% of the particles were less than 0.2

material as it occurred *in situ*; the mean water content being 31%, the mean P_2O_5 on a dry basis may be taken as 20%. Individual samples vary, and ordinarily there is a minimum in P_2O_5 in the middle of the section. This variation is correlated with the occurrence of the two bone beds in the chiropterite. The solubilities of the phosphate in water, citrate, and citric acid are believed to be in accord with the hypothesis that the upper zone of enrichment contains more brushite and the lower zone more "collophane." Two profiles are published and are here given in table 48.

The published evidence in favor of Schadler's statement about the general distribution of brushite is thus not entirely satisfactory, though not discordant with the distribution of citrate solubility. Schadler concludes that in the more superficial material of analysis V, about 8.18% $CaHPO_4 \cdot 2H_2O$, 44.36% "collophane," and 6.4% $CaCO_3$ are present, while in the deeper material of analysis VI (table 46), all the phosphate is present as "collophane."

Brushite certainly did occur in the chiropterite as minute colorless plates and was

TABLE 48

	SiO ₂	H ₂ O	CaO	P ₂ O ₅	Percentage of P ₂ O ₅ Soluble in:		
					H ₂ O	Citrate	Citric Acid
Field 1, zone 8 (Dafert and Höfinger, 1931)							
0.5 meter	43.10%	—	27.05%	22.58%	0.5 %	16.6 %	97.95%
1.0 meter	22.20	—	25.91	17.82	0.3	8.9	92.4
2.0 meters	17.58	—	32.66	27.05	0.2	7.4	70.3
3.0 meters*	49.92	—	1.48	13.26	0.1	34.5	7.9
Cave bear bones	0.58	—	42.11	33.89	—	9.8	87.8
Brushite from cave	—	—	35.78	39.55	1.8	96.6	97.6
"Collophane" from cave	—	—	50.54	36.48	—	14.3	96.9
Field 2, zone 23 (Dafert and Entres, 1931)							
0-1 meter, red brown	—	27%	—	18.41	0.03	32.26	59.92
1-2 meters, brown wet	—	25	—	20.16	0.03	33.78	94.74
2-3 meters, brown wet	—	25	—	18.80	0.07	27.65	76.86
3-4 meters, dark brown, crumbly	—	24	—	21.78	0.06	21.99	81.08
4-5 meters, brown	—	22	—	23.16	0.09	17.18	77.98
5-6 meters, gray brown layer above phosphate veins	—	20	—	17.60	0.01	1.65	2.45
6-7.5 meters, matrix of veins	—	16	—	10.38	0.02	19.74	3.47
6-7.5 meters, phosphate vein	—	20	—	43.59	0.08	89.08	4.22
Field 2, zone 18							
8 meters	—	23	—	16.41	0.01	14.68	69.04
N rich lens	—	29	—	13.21	0.004	19.30	96.67

* Most of the P₂O₅ of the 3-meter sample in this profile is obviously not present as a calcium salt and in part may be comparable to the material of the phosphatic veins at 7.5 meters in the profile below and in analysis IX of table 46.

identified crystallographically and chemically by Schadler and Armbricht, who give the following analyses:

CaO	33.13%	32.61%
P ₂ O ₅	41.20	41.34
H ₂ O <100° C.	17.20	26.25
H ₂ O red heat	8.78	

CaO	50.14%
MgO	0.05
Fe ₂ O ₃	0.57
P ₂ O ₅	41.55
CO ₂	0.83
H ₂ O <100° C.	2.32
H ₂ O 150°-200° C.	0.79
H ₂ O (org.?) >200° C.	3.78

According to Schadler's diagram of the distribution of minerals in the deposit, brushite occurred mainly in the superficial part of the inner end of field 2. A bed of a nodular calcium phosphate, termed collophane by Schadler and other investigators of the cave, occurred near the bottom of the deposit. The nature of the collophane, regarded as Ca₃P₂O₈·H₂O by Schadler, is obviously not entirely certain. The purest material, occurring as nodules 5 cm. in diameter, white internally but with a reddish superficial impregnation, gave:

A material also termed "collophane," forming a coating on limestone fragments, was also analyzed:

SiO ₂	3.71% (3.59 acid insol.)
TiO ₂	0.07 (all acid insol.)
Al ₂ O ₃	1.69 (0.57 acid insol.)
Fe ₂ O ₃	1.88 (0.06 acid insol.)
CaO	44.65
MgO	0.70 (0.11 acid insol.)
P ₂ O ₅	31.79
Cl	0.08
CO ₂	5.80
H ₂ O <100° C.	3.04
H ₂ O (org.) >100° C.	6.74

Some loss of CaO and enrichment in weathering products have clearly taken place in the formation of this crust.

It is noteworthy that no significant amounts of fluorine were discovered in the phosphate of the Drachenhöhle. It would, however, be interesting to know more about the sensitivity and accuracy of the method employed in the analysis of this element.

Part of the deposit certainly contains phosphates of elements other than calcium. Veins of phosphatic material occur in the sandy layer under the chiropterite in the middle of field 2. The analysis of this material is interpreted by Machatschki as implying that 50.87% of the phosphatic veins consists of variscite, though the identification is not regarded as certain. The absence of a potassium determination is unfortunate, but since the analysis accounts for 99.5% of the material present, it is unlikely that an appreciable quantity of taranakite was present. Aluminum is clearly enriched over iron in the phosphatic veins, as can be seen by comparing analysis IX with analyses II-IV. It is probable that small amounts of aluminum phosphate were present throughout the lowest layers of the deposit; Machatschki computes that at least 3.48% variscite was present in the material of analysis VIII. Small quantities of ferric phosphate were evidently present with the aluminum phosphate mineral of the phosphatic veins. Schadler indicates that ferric phosphate also occurs in a zone near the first rockfall continuous with the main scharizerite layer, but from which the dark organic mineral has been leached. About 3.5% to 5.5% Fe_2O_3 and 5.5% Al_2O_3 occur in the upper chiropterite.

Manganese is present in very small

amounts in the phosphatic earth. It is said to form a coating on the bones of the deeper layers and dendritic markings on those of the upper layers. This is, however, not true in the bleached zone where the manganese oxides may have combined with phosphates. Cinnobar red coloration may be attributable to the presence of a manganese phosphate.

The K_2O and Na_2O contents of the phosphatic earth are presumably due to the inclusion of mica, though it is possible potassium aluminophosphate (i.e., taranakite) may occur.

Silica, in part as quartz and in part as aluminosilicate minerals, constitutes 20% to 35% of the chiropterite and 35% to 75% of the underlying phosphatized sand and clay. Sulphur is present in quantities varying from 0.2% to 0.3%. The material of the bleached zone gives an odor of H_2S on treatment with acids. Microscopic gypsum crystals occur in consolidated crusts.

The water content of the sediments is very variable, ranging normally from 30% to 50% of the chiropterite, but considerably less in the basal layers. There is evidence that rapid movement of air in certain places in the cave is responsible for low water contents. The material below a sinter layer may have a significantly lower water content than does the material above such a layer. About 700,000 liters of water appear to reach the deposits annually. Such a rate would imply a complete replacement of the water of the sediments every five years. Actually in the upper layers, a quite rapid series of changes leading to replacement of water by air and air by water in the pore spaces of the deposit may occur, while in the deeper layers capillary water is probably held for much longer periods than

TABLE 49

	I		II		III	
Moisture	13.66%	13.62%	22.20%	22.07%	15.46%	—
Ash	54.46	53.94	16.40	16.05	17.70	17.62%
P_2O_5	9.01	9.06	0.396	—	2.36	2.27
C	17.77	17.40	34.79	34.65	35.33	35.58
H	2.43	2.61	4.38	4.20	4.30	4.46
N	6.76	6.65	7.53	7.67	8.16	8.24
C ash and moisture free	55.27	54.10	56.64	56.22	52.83	53.20
H ash and moisture free	2.80	3.37	3.09	2.82	3.86	4.08
N ash and moisture free	21.02	20.68	12.22	12.44	12.20	12.32

the mean rate of replacement would suggest.

Throughout the deposit of field 2 there occur dark bands which are referred to infiltration of an organic mineral termed scharizerite by Schadler and Lieb (1931). This organic mineral (I) is apparently a humic material greatly enriched in nitrogen. Similar materials containing less nitrogen occurred in the cavity in the wall of the cave (II) and in the skull of a cave bear (III). Analyses are given in table 49.

The material is presumably derived from the decomposition of animal tissue rich in proteins.

Schadler has considered the diagenetic changes in the deposits of the cave and the climatic interpretation of such changes. It must be remembered that, in studies of this sort, two sources of error need to be considered. At any given time changes in the movement of water through the deposits may produce effects throughout the entire thickness, so that the alternation of wet and dry phases leaves no stratigraphic record of climate. In practice, it would appear that this has happened in part of field 1 and in fields 3, 4, and 5, but not in field 2. The thinner deposits of fields 1, 3, 4, and 5, therefore, largely constitute modern profiles; those of field 2 are from the standpoint of pedology in part fossil. Since evaporation is greater at high temperatures than at low temperatures, a cold period may be indistinguishable from a wet, and a warm from a dry period.

Schadler considers that the existence of the dried-out cracked layer and of a marked decomposition of the limestone blocks in the lower part of the phosphatic deposit indicates the influence of the intervention of a more arid period on the deposits of a relatively humid period. Subsequently, after the formation of the layers of sinter platelets, infiltration with black organic matter (scharizerite), notably on the inner side of the first rockfall, suggests the effect of a later, more humid period after a more arid period. The humidity in the cave at this time was greater than it is today. Subsequent to this humid period, during which the upper bone bed and the scharizerite infiltrations were formed, but prior to the modern damp phase, there seems to have been one or more arid phases during which water was replaced by air in the pore

spaces or part of the deposit. Some of the scharizerite decomposed, producing bleached zones, and in other places the organic material formed dry hard nodules.

It is possible to interpret these changes in humidity within the cave, either as due to changes in precipitation or in evaporation, i.e., in temperature, outside the cave. The association of small mammals described by Wettstein from the middle layer of the chiropterite apparently suggests slightly warmer conditions than those of today, and, as the earliest and latest deposits presumably are latest Riss and earliest Würm, respectively, the wet periods are quite likely to be colder than they are today. Variation in temperature is therefore quite likely involved as much as, or more than, variation in humidity.

It is noteworthy that the greatest number of cave bear bones belong to the wetter, colder phases, but there is evidence from the horizontal distribution of bones that perennially damp conditions are more conducive to preservation than are conditions characterized by frequent dry periods.

GROSSE PEGGAUER FELSENHÖHLE

This cave lies in the Peggauer Wand in the Murtal above Graz. It is of irregular form, just under 100 meters long and with three entrances. The cave earth was impregnated with phosphate and contained many bones of *Ursus spelaeus*. The mean P_2O_5 content was 6%, but individual samples contained up to 17.6%. In 1928 it was estimated that 36 tons remained (Göttinger, 1928).

GLASERLUKE

A cave in the same cliff face, containing a deposit of cave earth 20 meters long, 8 meters wide, and of mean depth 2 meters, maximum depth 3.5 meters. The material was free from bones and practically free from rock fragments. The mean phosphate content was 4% P_2O_5 , and in 1928 10 tons of P_2O_5 were estimated as present (Göttinger, 1928).

BADLHÖHLE

In the Badlgraben, a side valley of the Mur above Peggau, containing a markedly stratified deposit. An upper layer, earthy gray brown at the top and more stony lower down, contained in general 9% to 14% P_2O_5 ,

rarely up to 16.37% P_2O_5 . This was separated by water-borne sand, free of phosphate, from 4 meters of brown earthy and yellow clayey layers containing about 1% P_2O_5 . Cave bear bones were numerous. The total P_2O_5 content was estimated in 1928 as 58 tons, of which 28 had been removed (Götzinger, 1928). The mean content of the deposit was about 7%.

KAPELLENHÖHLE

North of the chapel on the road between Peggau and Bruck, probably communicating with the Badlhöhle. The concentration (1.8%-5.4% P_2O_5) and distribution of the phosphate are said to have been similar to those of the deposit in the Badlhöhle. Only 33 tons of phosphatic earth containing a mean amount of 4% P_2O_5 , and so corresponding to 1.3 tons P_2O_5 , were estimated as present (Götzinger, 1928).

REPOLUSTHÖHLE

In the same valley as the Badlhöhle, containing phosphatic earth and bones, but also more rock debris than in the deposits of the Badlhöhle. The cave earth is said to be very fine and dry, but an analysis of a sample from a depth of 3 meters gave 22.65% H_2O and 16.78% P_2O_5 . Other samples contained 2% to 3% P_2O_5 , and the mean content is given as 5%. The original reserve was estimated as equivalent to 10 tons P_2O_5 (Götzinger, 1928).

ARZBERGHÖHLE, WILDALPEN

A complex cavern with chambers at several levels. In the highest of these, stratified phosphatic earth with cave bear bones occurred. The phosphate had, however, been partly washed down into the lower levels. Two analyses are given:

METERS	H_2O	P_2O_5	P_2O_5
		% WET WEIGHT	% DRY WEIGHT
0.35	31.93%	5.99%	8.80%
1.30	33.87	11.31	17.10

The total original reserve was estimated as 7.30 tons P_2O_5 (Götzinger, 1928).

BÄRENHÖHLE, HIEFLAU

A large cave in Hartlesgraben at an altitude of 1116 meters above sea level. It pene-

trates 450 meters with an average width of 10 meters. The earth of the floor of the innermost hall is rich in phosphate, and there was a phosphatic filling between rocks in the first chamber of the cave. In places the earth reached the roof of the cavern. It was very rich in the bones of cave bears. As in the Drachenhöhle, phosphatic incrustations containing up to 26.34% P_2O_5 occurred, as well as consolidated phosphate, described as colophane. The brown or red brown dry earth contained up to 17.12% P_2O_5 , the mean content being 10% P_2O_5 and the total reserve about 240 tons P_2O_5 (Götzinger, 1928).

Götzinger lists 31 other Styrian caves as containing phosphatic earth. Analyses are given in the case of 17 caves, and these indicate that in 10 deposits less than 1.0% P_2O_5 was present in the richest sample analyzed. Three other caves yielded material containing 1.0% to 1.99% P_2O_5 , and one yielded material between 2.00% to 2.99%. The Mathildengrotte south of the Drachenhöhle in which a red cave earth containing bones of *Ursus spelaeus* and up to 3.3% P_2O_5 occurred, the Ochsenloch, a rock shelter at Köflach, yielding a deposit containing 16.92% H_2O and 3.61% P_2O_5 , and the Weissenbachhöhle St. Lorenzen, containing up to 5.36%, are the only three of these caves of any importance as sources of phosphate. The estimated reserve never exceeded 5 tons P_2O_5 , the figure for the Ochsenloch. Cave bear bones occurred in four of these caves, including the Mathildengrotte. A single nitrogen analysis is given for Katerloch, Weiz, a cave yielding a deposit with 0.36% to 0.98% P_2O_5 and 1.72% N.

CAVES IN CARINTHIA

A few caves appear to contain modern coprogenic deposits.

EGGERLOCH, VILLACH

About 10 tons¹ of bat guano containing up to 2.68% P_2O_5 is said to have been present. This corresponds to about 0.2 ton P_2O_5 .

LAMPRECHTSKOGELHÖHLE, VÖLKERMARKE

Said to have contained 20 to 30 tons of badger excrement giving on analysis 0.82% to 1.24% P_2O_5 and 0.52% N.

¹ One wagon equals apparently 10 tons.

TSCHERNERWANDHÖHLE

Said to have contained 10 to 20 tons of chamois and bat guano, giving on analysis 0.75% to 1.44% P_2O_5 and 3% N.

In addition, there appear to be a few caves containing slightly phosphatized cave earth, the distribution of maximum contents being:

1.00%-1.99%	1
0.1 -0.99	2
Tr.	4

CAVES IN LOWER AUSTRIA

About 500 caves have been explored. Of these Dachluken, Lunz, and Taubenloch, Oestcher, are said to have contained dove guano, the latter locality, with an estimated reserve of 100 kilograms, containing 1.85% P_2O_5 .

Bat guano is said to have occurred in Geldloch, Oetscher, Gaming, a deposit 1 meter high containing 1.24% P_2O_5 ; Kollerhöhle, Gösing, *ca.* 50 tons containing 0.51% to 0.83% P_2O_5 ; Rodlerhöhle, Waldegg, *ca.* 200 tons; Stefaniehöhle, Waidhofen, on the River Ybbs, *ca.* 300 tons containing 1.11% to 1.39% P_2O_5 .

Unspecified guano is said to have occurred in the Höllturmhöhle, Wollersdorf, where about 30 tons of deposit mixed with debris contained 1.43% to 2.88% P_2O_5 and 6.18% N.

Cave bear bones occurred in only three or four localities and in one cave, the Rötelloch, 3 cubic meters of a reddish earthy material containing P_2O_5 are said to have yielded recent rodent bones.

The Fuchs or Teufelslucke, near Eggenburg, a locality yielding a few Solutrean or Magdalenian artifacts and an important series of mammalian bones, but no fossil bats, contained earth yielding only 1.4% to 1.8% P_2O_5 (Sickenberg, 1932).

Of the other caves, presumably containing ancient material, one, the Schwarzgrabenhöhle in the Hohen Wand near Mayersdorf, contained from 0.89% to 5.05% P_2O_5 , the reserve being only 6 tons P_2O_5 ; one cave, the Merkensteinerhöhle near Baden, from 3.64% to 4.85%, the reserve being 6.6 tons P_2O_5 .

The maximum phosphate concentrations in the minor deposits recorded are distributed as follows:

2%-2.9%	4
1 -1.9	13
0.1 -0.9	6
Tr.	8
No analysis	4

The only large deposit was at Nixloch, Frankenfels, where 160 tons of P_2O_5 may have been present, though the mean concentration was only 2%. In addition to the nitrogen analysis of the guano of the Höllturmhöhle, a nitrogen determination of 1.47% with a phosphate of 1.23% is given for a small and probably old deposit at the Herdenglhöhle, Lunz. The entire phosphatic deposits of the caves of lower Austria are not likely to have exceeded 235 tons P_2O_5 , of which 160 were in the Nixloch.

LETTENMAYERHÖHLE, KREMSMÜNSTER

Schadler (1920) has described the deposits of this cave, one of three that lie about three-quarters of a kilometer north of Kremsmünster in upper Austria. The cave opens at the base of a slope cut in glacial deposits, as follows:

METERS		
7.0	Gray nagelfluh (conglomerate)	Mindel
0.1	Clay	First
		Interglacial
5.0	White nagelfluh (conglomerate)	Gunz
2.0-3.0	"Sandlasse"	
10.0	Conglomerate	

which overlie Miocene beds. The cave is excavated in the "Sandlasse." It forms a large hall 24 meters long in an east-west direction, 20 meters broad in a north-south direction. The floor of the cave is flat, and the distance between floor and roof is about 1.2 meters in the northeast, increasing to 1.7 meters in the southeastern part. The cave deposits were about 1.8 meters thick, and the southeastern part of the floor was covered with a layer of coarse calcite dripstone about 0.5 meter thick. The cave earth in part covered by this calcareous sinter was clearly stratified, the gray layers containing less and the brown layers more P_2O_5 (fig. 94). The material richest in phosphate was yellow brown. A gray phosphate-poor layer was interstratified between rich brown layers in the northwestern

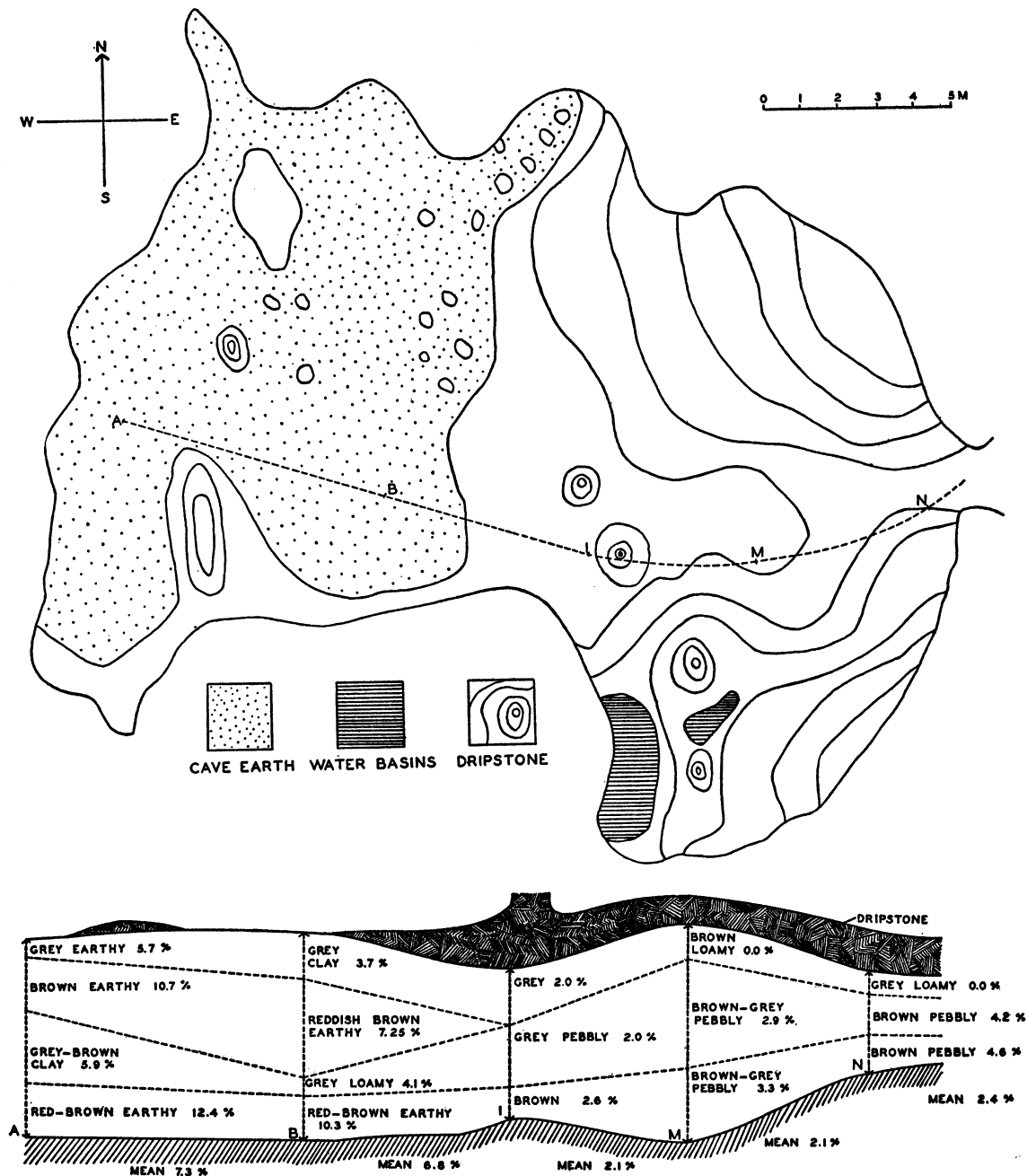


FIG. 94. Plan and section of the Lettenmayerhöhle. After Schadler.

part of the deposit. The phosphatic material in the northwestern parts of the deposit was more friable than that in the southeastern part. About 350 m³, or 420 tons, of the deposit contained 7% P₂O₅ and 150 m³, or 180 tons, contained 3% P₂O₅. The total P₂O₅ con-

tent was set at 35 to 40 tons. Göttinger (1928) indicates that 10 tons had been removed at the time of his writing and that 25 tons remained. A poorer material filled an extension of the cave which was formerly its entrance.

Schadler indicates that remains of at least

75 cave bears had been found early in the exploitation of the cave. Using data supplied by Abel for the probable phosphate excretion of a cave bear (5.0 to 7.5 kilograms per year, of which 10% was deposited in the cave) he concludes that the whole of the deposit could be produced in 40,000 to 50,000 years by a stationary population of three bears.

Götzinger (1928) lists 18 caves in upper Austria containing phosphatic earth, but in none of the seven analyzed deposits does the material contain over 2% P_2O_5 . The Dachsteinrieseneishöhlen provided a deposit containing small mammal bones; unfortunately these were not determined. Cave bear bones, possibly washed in, occurred in another part of this system.

BÄRENHORST, UNTERSBERG, SALZBURG

An irregular cave at an altitude of 1550 meters. A large hole, termed the Bärenschacht and presumably yielding cave bear bones, lies near the entrance, and farther in at a higher level is a chamber which contained a deposit of stratified cave earth overlain by debris. The maximum thickness of this deposit was 7 meters. The phosphate content varied from 8.0% to 10.26% P_2O_5 , and the whole deposit was equivalent to about 72 tons P_2O_5 . An adjacent cave, the Gamslöcher, communicates with the Bärenhorst, but its cave earth contained but 2.36% to 2.68% P_2O_5 , and the whole reserve was only about 7 tons P_2O_5 .

Thirty-three other caves in the province of Salzburg are listed by Götzinger, the maximum contents of P_2O_5 being distributed as follows:

3-3.9%	1
2-2.9	1
1-1.9	10
0.1-0.9	7
tr.	14

CAVES IN TYROL AND VORARBERG

The Tischoferhöhle, Kufstein, yielded phosphatic earth containing up to 5.13% P_2O_5 . Cave bear bones were present, but the estimated reserve of phosphate was only 2.4 tons. Twenty-six other caves appear to have some phosphate of ancient origin, the distribution of maximal values being:

2.00-2.99%	1
1.00-1.99	7
0.1-0.99	5
tr.	13

Six caves other than the Tischoferhöhle appear to have yielded bones; three of these had slightly phosphatic earth, a trace in one cave and 0.57% in the other two.

In addition, three caves are recorded as containing modern coprogenic deposits: Fuchsloch, in the Thaurerschluft, near Hall, bat guano containing 2.49% P_2O_5 ; Schafgut, Hundsalz (Pendlingstock), sandy earth and sheep dung, trace of phosphate; Wirtshofhöhle, Erfsendorf, rock shelter with guano.

CZECHOSLOVAKIA

VYPUSTEK AND OTHER CAVES NEAR BRNO

Frodl (1923) has described the occurrence of phosphatic cave earth northeast of Brno. Thirteen caves in all appear to have been investigated, but only three proved to contain more than 4% P_2O_5 in their deposits. These three, the Vypustek, Dratenikova, and Jäckýmka Caves, lie in the Kiriteinerthal, about 6 kilometers north-northeast of Brno. The best-known and largest deposit was in the first-named cave.

The Vypustek Cave is a cavern with fairly complex series of galleries near the entrance and a long gallery opening from the complex region about 100 meters from the entrance and running back about 250 meters. In the beginning of this gallery is a large chamber, the Bären-Halle, in which the main deposit occurred. A longitudinal section (fig. 95) of the chamber indicates the general stratification observed. The most striking feature of the profile is evidence of a period of rockfalls in the middle part. There are indications of a minimum in phosphate in the middle strata also, but this minimum, if real, is poorly marked. Cave bear bones have been obtained in numbers from the deposit, but other mammalian remains are rare. The cave has yielded phosphate equivalent to 1200 tons of P_2O_5 . Frodl concludes that, since each bear weighing about 500 kilograms would contribute at death about 8 kilograms of P_2O_5 to the deposit, it is unlikely that the phosphate was produced solely from dead bears. He also

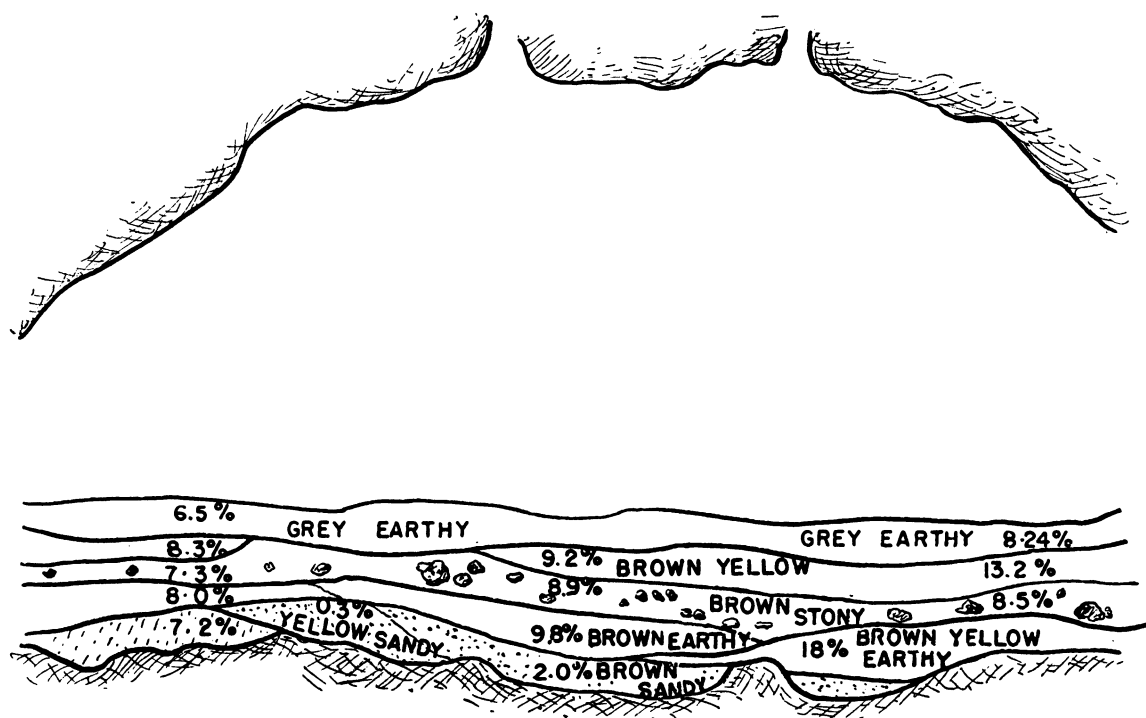


FIG. 95. Section through Vypustek. After Frodl.

considers, following Abel, that each bear would excrete 5 to 7 kilograms of P_2O_5 annually, and that most, supposedly 90%, would be lost outside the cave. Continuous habitation of the cave by three bears would therefore require a period of the order of a million years to produce the deposit. This is obviously impossible. Though the similar later computations of Schädler relating to the Drachenhöhle use rather different initial figures, Frodl's argument is certainly valid. Frodl thinks that most of the P_2O_5 is derived from necrotic material carried into the cave by water. It is curious that he did not suggest that the phosphatization was due to bats. Six species of bats are listed by Wolf (1934-1935) from the cave, but their occurrence is irrelevant to the formation of the ancient deposit. Analysis of the best material as used commercially gave:

Hygros. H_2O	10.86%
H_2O of hydration	2.73
Organic (humus)	1.68
N	0.15
P_2O_5	11.41
CO_2	3.51
SiO_2	0.28
CaO	18.07

K_2O	0.42
Na_2O	0.31
$(Al, Fe)_2O_3$	6.24
MgO	0.64
Mn_2O_4	0.09
Insol. residue	43.67

It would appear that calcium phosphate must have accounted for more than half the water-free, acid-soluble material. Three specimens containing from 2.51% to 12.19% P_2O_5 were extracted with citric acid, and 88.44% to 94.33% of the phosphate was found to be soluble.

Two samples were fractionated by mechanical analysis, and the phosphate of the different fractions was determined:

	PER CENT	TOTAL P_2O_5 IN FRACTION	CONTRI- BUTION TO WHOLE
> 5 mm.	6.05%	6.08%	0.368
2-5	2.86	10.77	0.308
1-2	2.88	13.80	0.397
0.5 -1	2.26	13.16	0.297
0.2 -0.5	6.60	11.68	0.771
0.05-0.2	26.45	9.39	2.484
0.05	52.90	8.63	4.568
			9.193

	PER CENT	TOTAL P ₂ O ₅ IN FRACTION	CONTRI- BUTION TO WHOLE
>5	4.32	13.11	0.562
2-5	3.60	16.59	0.598
1-2	1.78	14.71	0.263
0.5-1	1.89	13.66	0.258
0.2-0.5	6.03	11.84	0.714
0.05-0.2	23.14	7.97	1.844
0.05	59.24	9.64	5.713
			9.952

No details are given about the other deposits save that from the Drátenikova Cave 120,000 kilograms of P₂O₅ and from the Jäckýmka Cave 25,000 kilograms of P₂O₅ had been removed. A sample of cave earth from the latter contained 15.45% P₂O₅, of which 87.89% was soluble in citric acid.

STAUPERHÖHLE

Tod (1859) gives an analysis from this Moravian cave, the exact position of which could not be ascertained:

Moisture	23.42%
Nitrogenous organic matter	52.30
Humic and carbonaceous matter	4.21
Total N	9.42
N·NO ₃	0.11
N·NH ₃	6.02
Na ₂ O	1.56
K ₂ O	
CaO	
MgO	
Fe ₂ O ₃	0.14
P ₂ O ₅	2.30
Cl	0.28
SO ₃	2.42
Sand, SiO ₂	2.09

A sample from an undesignated locality in the Carpathians is said by Moser (1878) to have contained 20% H₂O, 2.14% P₂O₅, and 7.60% N, of which 0.77% was as nitrate.

Moser also gives two analyses for material from caves at Ozsowa. It has not been possible to identify this locality, which probably lay in the Slavonic part of the old Austro-Hungarian Empire.

H ₂ O	11.51%	9.20%
N	8.16	5.14
P ₂ O ₅	1.73	5.04

These somewhat miscellaneous analyses have proved useful in the construction of figure 96, which gives the relation of nitrogen to

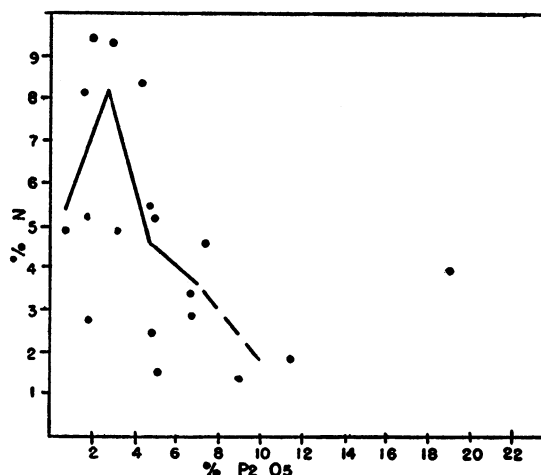


FIG. 96. Relationship of total nitrogen to phosphate in Central European cave guanos.

phosphate in the cave guanos of Rumania, Hungary, Austria, and Czechoslovakia.

POLAND

OJCOW

A number of caves in oolitic limestone northeast of Cracow have been dug for phosphate. Römer (1884) specifically mentions the cave of Jerzmanowice or Fledermaus Grotto, the cave of Kozarnia or Ziegenstall, and the cave of Gorenice. The last-named cave had produced about 50 tons of phosphatic earth, but much more than this amount remained. The cave earth of these caverns contained bones of *Ursus spelaeus* and other fossils. From the Jerzmanowice Cave, Römer records in his osteological faunal list *Plecotus auritus*, *Pipistrellus pipistrellus*, *Eptesicus serotinus*, and *Myotis myotis* (sub *V. murinus*). Unfortunately there is no indication as to whether these bat bones were recent or fossil; all species except *E. serotinus* were abundantly represented. The German name of the cave indicates a bat colony, probably mainly of *M. myotis*. The unctuous dark brown earth between angular blocks of limestone said to form the cave floor may well in part have been recent bat guano.

GERMANY

It is probable that a number of caves in Germany that have yielded vast numbers of bones of cave bears also contained chiropterite. In most cases these caverns were probably

worked out before investigations other than those of paleontologists had been undertaken. Cuvier (1835) indicates that the yellowish earth of the famous bone cave at Gailenreuth, near Muggendorf in Bavaria, was analyzed for him by Laugier and was found to contain 21.5% calcium phosphate, presumably implying 9.9% P_2O_5 . Fraas (1872) indicates a somewhat more phosphatic cave earth in a cavern in the Höhlenfels, Schelklingen, which contained 18.89% P_2O_5 . He states that only the damp cave earths of the Swabian caves contain bones; it is therefore possible that some of the phosphate of apparently boneless caves is actually derived from decomposed bones, and not from chiropterite. The most interesting German occurrence, however, relates to an earlier period than the majority of bone caves.

GUNDERSHEIM, RHENISH HESSEN

Heller (1936) has described deposits that were apparently formed as cave earth in a collapsed limestone cavern. The cave earth now is found in isolated fissures which represent but portions of the original cave. No systematic stratigraphic account is given, but the most interesting deposit was material that partially filled a section of the ancient cave and consisted of white crusts of calcium phosphate, a thin black coating on this phosphate, and numerous bat bones. No chemical details are given, but it is reasonable to assume that this material was formed from bat guano and dead bats. The commonest species appear to have been a *Rhinolophus* near *ferrum-equinum* Schreber but somewhat smaller, *Myotis kormosi* near the living *M. bechsteinii*, and *M. exilis* near the living *M. daubentonii*. The associated fauna indicates a lower Pleistocene date and is referred to the Lower Cromerian by Heller, i.e., to a section of Pleistocene time prior to the Antepenultimate or Gunz-Mindel interglacial.

FRANCE

The oldest information relating to bat guano in French caves is probably that given by Mangon (1857) who analyzed material brought from a cave near Des Petits Andelys, department of Eure, Normandy. This cave is the most northern bat cave in France from which guano has been recorded. The analyses

are reproduced below. The most extensive source of data on the occurrence of bat guano in French caves is to be obtained from the papers entitled "Biospéologica, Enumération des grottes visitées" (Jeannel and Racovitza, 1907, 1908, 1910, 1912, 1914, 1918, 1929). Since bat feces form an important source of food for cave animals, and since the association found feeding on such material differs when isolated droppings such as are usually produced by *Rhinolophus* are compared with the more massive deposits formed by colonies of *Myotis* or *Miniopterus*, notes as to the occurrence of guano were evidently regarded as essential entries in the description of a cave, and most, if not all, of the caves for which no data as to guano are given may be regarded as lacking deposits. The general distribution of caves containing at least a small deposit of guano, as opposed to mere scattered bat dung, is as follows:

	TOTAL CAVES EXAMINED	NUMBER WITH GUANO
Alpine Massif westward to Rhône:		
Haute Saône	2	1
Doubs	11	1
Cote d'Or	4	0
Yonne	2	1
Jura	1	1
Ain	3	0
Isère	5	1
Drôme	18	3
Basses Alpes	1	0
Alpes Maritimes	11	1
Var	2	0
	60	9 (15.0%)
Western France, Cen- tral Massif and Cen- nnes eastward to Rhône:		
Mayenne	3	0
Dordogne	6	0
Lot	9	0
Aveyron	2	0
Ardèche	18	5
Gard	20	9
Hérault	17	2
Tarn	7	3
Tarn et Garonne	9	1
	91	20 (22.0%)

	TOTAL CAVES EXAMINED	NUMBER WITH GUANO
French Pyrenees:		
Aude	15	2
Pyrénées orientales	17	4
Ariège	42	13
Haute Garonne	15	3
Hautes Pyrénées	22	5
Basses Pyrénées	36	6
	147	33 (22.4%)

There is evidently a slight deficiency of guano deposits in the more northern caves of the Alps. The percentage figures for the French Pyrenees and for the whole of France, namely, 20.8%, are of the same order of magnitude as those for the Spanish Pyrenees and are markedly lower than those for the south of Spain (p. 451). The Pyrenean figures contrast strongly and curiously with the statement of Casteret (1939) that he had encountered bat colonies in only about 10 of some 500 caves investigated.

The principal species of bats forming true guano deposits in France appear to be *Myotis myotis*, *M. oxygnathus*, and *Miniopterus schreibersii*. The first-named species is doubtless the most important, but in the relatively few records of bats that have been published as a result of the Biospeologica investigation, only *M. oxygnathus* and *M. schreibersii* are noted. The former species is recorded only from Barrenc de Prapérié, Bugarach, Aude, in which a few specimens occurred and in which guano is not specifically mentioned. *Miniopterus schreibersii* occurred abundantly in September in the Grotte du Mas d'Azil, Ariège, which is probably a guano cave though in its drier parts the bat dung is said to turn to dust and so not form a deposit; in the Grotte inférieure du Queire, Biert, Massat, Ariège (fig. 97) in which both old and fresh guano occurred; in April in the Grotte de Mollans, Buis-les-Baronnies, Drôme, in which there are probably only scattered droppings; in March in the Grotte de Pialoux, Peyrus, Chabeuil, Drôme, in which no guano is recorded; in November in the Grotte de la Coquille ou de Minerve, in which a vast colony of the species occurs and produces guano; and in December in the Grotte de Senchet, Penne-du-Tarn, Vaour, Tarn, in

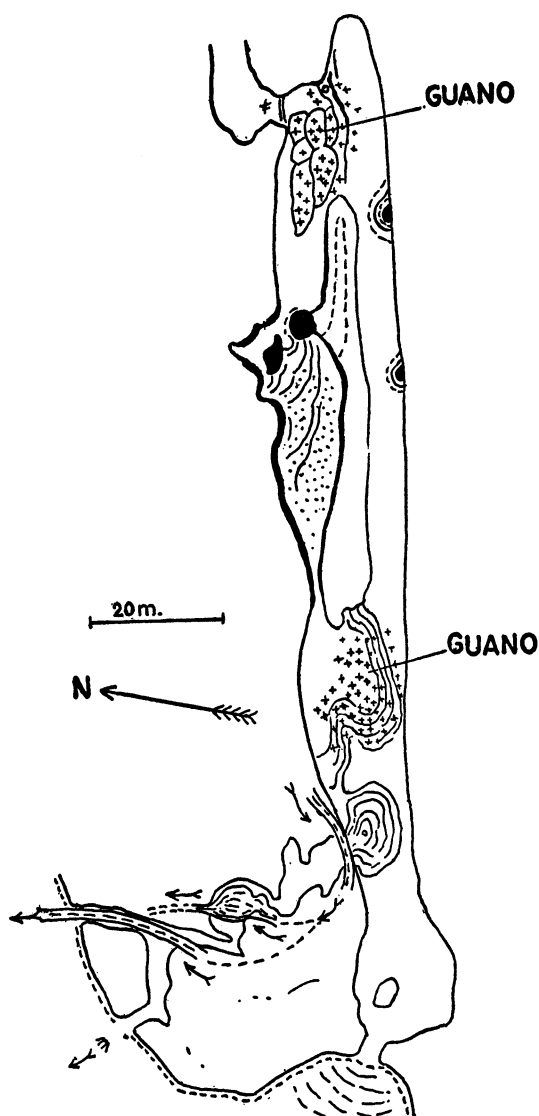


FIG. 97. Grotte inférieure du Queire. After Jeannel and Racovitza.

which no deposit is recorded. The last two records at least must refer to winter aggregations. These data presumably give too great prominence to *M. schreibersii* as a guano producer.

In the department of Ardèche, several caves visited in January lacked bats (Grotte du Soldat, Grotte de Remène) or contained very few (Grotte de Peyroche), but small heaps of guano indicated colonies at other times of year. A similar situation was observed in a small chamber opening off the

Grotte du Rendez-vous de Chasse, Matelles, Hérault, and in the Grotte de la Calmette, commun d'Allègre, Saint-Ambroix, the Baume des Italiens, Méjeannes-le-Clap, Barjac, and the Grotte de Tharaux, Barjac, in the department of Gard. In the last-named cave, bats were present in quantity in August. In the departments of Tarn and Tarn et Garonne the Grotte des Chauves Souris de Janoy, the Grotte de Cabéou, and the Trou de Capuchin likewise were found to contain heaps of guano but no social bats in Decem-

the region of the cave illuminated from the entrance. The cave is very wet, and the floor beneath the colony is covered with guano mixed with clay. The Grotte des Cavottes, Montrond, Quingey, is a very long, complex cave evidently possessing a considerable deposit in a dry passage; in January, 1917, a new deposit far in the cave was being formed by numerous bats hanging from the roof. The map (fig. 98) indicates the depth and complexity of the passages that bats may frequent. Bats are also said to be abundant in

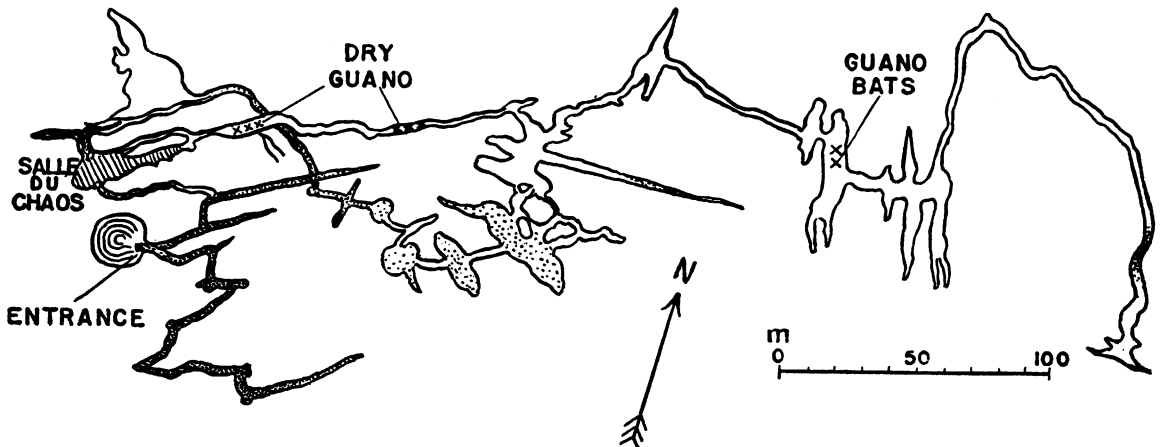


FIG. 98. Plan of Grotte des Cavottes. After Jeannel and Racovitza.

ber. In the department of Haute Garonne, the Grotte de Ganties and the Grotte d'Arbon, visited September 17-18, 1912, both contained guano heaps without social bats. It appears probable that most of the southern French caves containing guano deposits are the summer residences of reproducing females and that *Myotis myotis* and perhaps *M. oxygnathus* make up a large part of these female populations.

Jeannel and Racovitza summarize what is known about the bats in the caves of the department of Doubs; they mention *Miniopterus schreibersii* as well as *Rhinolophus ferrum-equinum* and other species that are less likely to be social, but not *M. myotis*. Considerable amounts of guano occur in caves in this part of the French Alps. The Grotte Sainte-Catherine, 2 kilometers below Consolation, Laval, Russey, is said to have an extremely large bat colony, localized in

the Grotte de Beure, Besançon Sud; the floor of this cave is covered with fallen rocks between which guano and bat bones occur.

It is clear that the Grotte Sainte-Catherine contains a large bat population in August, while in the Grotte de Beure there apparently are numerous bats in April. It is evident from the observations on these three bat caves that in this region large guano-forming populations can occupy caves at any time of year. It is unfortunate that no determinations of the species were made, as the department of Doubs is very near the northern range of *M. schreibersii* but well within that of *Myotis myotis*.

Few analyses of French bat guano have been published. Mangon (1857) gives two (I, II) of the deposits at Des Petits Andelys, in Normandy, and Weigelt (1879) an analysis (III) from an unspecified locality in Alsace Lorraine:

	I	II	III
Moisture	19.50%	12.66%	—
Organic and volatile	70.83	75.17	—
Total N	8.18	9.03	10.40%
CaO	2.37	2.74	—
MgO	0.02	0.02	—
K ₂ O	—	—	1.59
P ₂ O ₅	2.58	2.39	3.00
SO ₃	0.09	0.17	—
Sol. salts (including some phosphate)	2.42	1.83	—
Sand and SiO ₂	2.13	4.97	—

Although it is probable that a considerable proportion of the rather large number of French caves containing bat guano have been exploited by local agriculturalists, few records

caves, and in some cases this is probably chiropterite. Jeannel and Racovitza mention the Baoumo de la Campana, Saint Martin d'Ardèche, Bourg Saint Andiol, a cave 60 meters long and in which guano is still formed, as having been disturbed by phosphate exploitation. The Grotte de Gazel, Sallèles-Carbardès, Conques, department of Aude, is also said to have yielded phosphate, as is the Baume Sourde, Saou, Crest Sud, department of Drôme, though the phosphate of the last-named cave is said to have consisted of fossil bones.

The most remarkable phosphate deposit in a French cave is, however, that in the following.

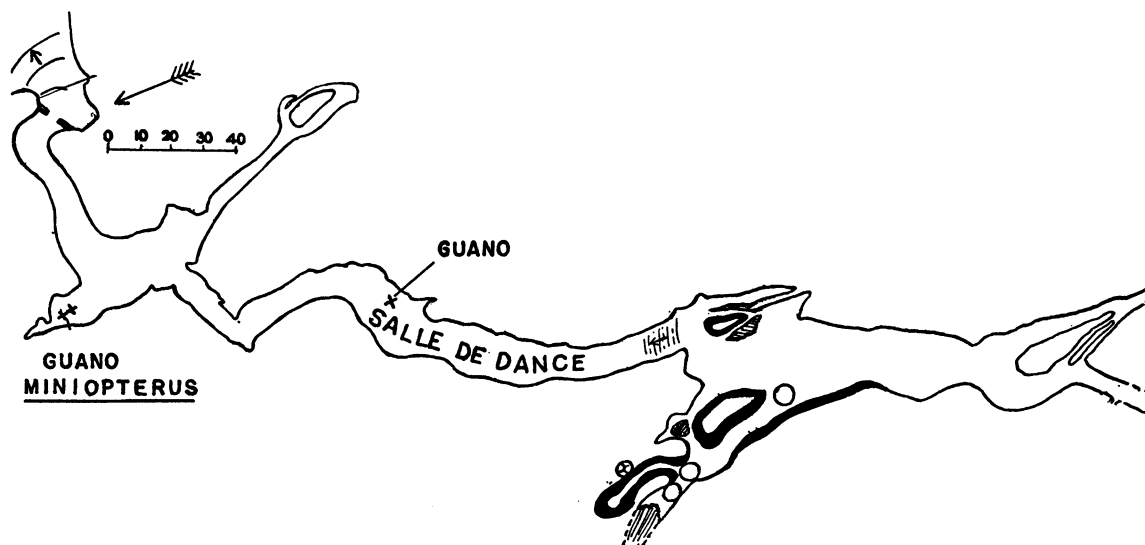


FIG. 99. Plan of Grotte de la Coquille ou de Minerve. After Jeannel and Racovitza.

of such exploitation are available. Jeannel and Racovitza, however, specifically indicate that the Grotte de Baume-des-Messieurs, at the beginning of the Dard Valley, Baumeles-Messieurs, Voiteur, Jura, had a large bat colony in September, 1907, but little guano, as most of the deposit had been removed. They also indicate the Grotte du Sureau, Castelvieu, Sainte-Anastasie, Saint Chapte, Garde; the Grotte D'Isturits, La Bastide-Clairence, Basses Pyrénées, and Grotte de Tourtouse, Sainte Croix de Volvestre, Ariège, to have been exploited.

Phosphate has been dug in certain French

GROTTE DE LA COQUILLE OU DE MINERVE

This very interesting cave lies near the village of Minerve, Cesseras, Olonzac, in the extreme southwest of the department of Hérault. The terrain here consists of hills capped with arid plateaus, locally termed "causses." The upper part of these hills consists of a middle Eocene nummulitic limestone. In the gorge of the River Cesse, this limestone can be seen to lie on a Paleozoic crystalline silicocalcareous rock with an irregular surface. A layer of residual reddish or bluish clay with concretions of gypsum and calcium carbonate lies between the Eocene

and the Paleozoic; this layer is of variable thickness and tends to fill the irregular depressions in the surface of the latter. The basal part of the limestone is fissured and cavernous, and the Grotte de la Coquille is one of the larger of these cavities. The floor of such caverns consists of the residual material lying on the Paleozoic; the walls and roof are of Eocene limestone (Gautier, 1894).

The cave consists of a long gallery which appears to extend more than 400 meters from its entrance into the hillside. A small recess on the right and a large passage on the left open out of the main gallery about 80 meters from the entrance. The recess is regarded by

Jeannel and Racovitza (1918) as the "cité permanente" of the vast population of *Mini-apterus* which now inhabits the cave, but, perhaps only in winter, small colonies enter the large corridor of the middle part of the cave, which is termed the "Salle de Danse" (fig. 99). It was in this region that the main phosphate deposit seems to have occurred.

The cave earth of the surface of the floor of the gallery is described as a mixture of calcium carbonate concretions, sand, and clay, with calcium phosphate in some places being the preponderant constituent, and with some aluminum phosphate. This layer, which was from 0.1 to 0.5 meter thick, contained

TABLE 50
DEPOSITS OF THE GROTTÉ DE LA COQUILLE OU DE MINERVE

	I	II	III	IV	V	VI	VII	VIII
H ₂ O	5.81% (120°C.)	8.78% (170°C.)	11.75% (175°C.)	8.46% (110°C.) 3.60 (180°C.)	9.67% 19.66	26.52% (160°C.)	23.70%	28.73%
Organic and water at red heat	4.33	5.24	5.43	9.76	—	8.23	4.50	
Na ₂ O	—	—	—	0.42	—	—	—	0.30
(NH ₄) ₂ O	—	—	—	—	—	—	0.52	0.47
K ₂ O	—	—	—	—	—	—	8.28	7.00
MgO	tr.	0.106	tr.	0.70	tr.	tr.	0.33	—
CaO	17.66	44.59	16.24	19.71	33.69	6.75	1.40	0.35
CuO	—	—	—	0.008	—	—	—	—
ZnO	—	0.149	—	—	—	—	—	—
PbO	—	tr.	—	tr.	—	—	tr.	—
MnO	—	—	—	tr.	—	—	—	—
Al ₂ O ₃	4.45	0.61	24.29	15.70	2.75	18.62	18.59	21.60
Fe ₂ O ₃	—		tr.	1.28	tr.	1.22	0.83	0.50
CO ₂	1.76	2.26	—	1.25	0.34	tr.	—	—
P ₂ O ₅	14.18	34.79	27.59	30.27	28.11	28.36	37.28	40.40
As ₂ O ₃	—	—	—	tr.	—	—	—	—
SO ₃	6.65	0.28	tr.	0.21	2.47	tr.	tr.	—
Cl	—	0.065	0.00	0.02	0.21	0.00	tr.	—
F	0.90	0.85	2.10	1.55	1.71	0.44	tr.	0.15
Silica	45.25	2.16	13.10	{2.05}	2.55	9.89	4.35	0.54
Sand and clay				{4.83}				

- I. Top 4-5-meter mean sample of reddish phosphatic earth.
- II. Bone from phosphatic earth.
- III. Yellowish concretionary rock below 3-4 meters.
- IV. Grayish phosphatic rock marked with pink and with calcareous veins.
- V. Dove gray friable rock below surface of the Galerie des Tribunes.
- VI. Bluish clay-like material, density about 0.49, contact with Paleozoic rock.
- VII. Minervite (Carnot, 1896), trace of Pb recorded from comparable sample, which also contains Rb, by Bannister and Hutchinson (1947).
- VIII. Minervite (Gautier, 1914).

from 2% to 18% P_2O_5 . Below this, to a depth of 2 or 3 meters, large numbers of fossil bones were found, *Ursus spelaeus* being the dominant species represented. These bones were embedded in a reddish cave earth of variable composition, the analysis (I; see table 50) given representing the mean of 20 specimens. As in the case of the superficial layer, the cave earth contained calcareous concretions and small veins of gypsum. An analysis (II) is also given by Gautier of a dorsal vertebra of *Ursus spelaeus*. This analysis is of interest on account of the presence of zinc and traces of lead in the bone. Gautier supposes that these represent traces accumulated during life.

Below the cave earth with its bones, the deposit becomes harder, forming a concretionary rock, yellow or sometimes pinkish or blackish gray in color, a layer from 2 to 9 meters thick. The analyses (III-VI) of this phosphate rock indicate that a variable but often considerable amount of the phosphate is present as an aluminum phosphate; Gautier concludes that, in the case of V, 6.58% of the material is $AlPO_4$, in the case of VI, 37.97%. This figure may be a little low, as he supposes the calcium to be present as $Ca_3P_2O_8$, which is unlikely, a slightly more basic apatite being probable. In general, there seems to be a very great excess of Al_2O_3 over Fe_2O_3 in this locality. It is not possible, in default of analyses of the residual material at the base of the limestone and of other probable sources of sesquioxides, to ascertain whether this excess is due to the nature of the parent material or to the migration of aluminum into the phosphatized parts of the cave earth.

Brushite occurred as a pulverulent crystalline mineral or forming friable masses around nuclei of unaltered limestone, both on the surface of the deposit and in fissures in some of the galleries.

The following analyses are given, I corresponding to fresh material, II and III to material dried in air for 18 months:

	I	II	III
$H_2O - 160^\circ C.$	19.17%	21.53%	21.92%
$H_2O + 160^\circ C.$ and trace organic matter	7.88		
P_2O_5	40.05	41.41	40.58
SO_3	tr.	tr.	tr.

CO_2	tr.	1.35	1.20
CaO	30.70	34.04	33.42
MgO	tr.	tr.	tr.
Al_2O_3	1.94	1.70	2.10
Silica, clay, etc.	0.01	0.15	0.76
Fe_2O_3 , nitrates, etc.	tr.	tr.	tr.

The first analysis corresponds to $CaHPO_4 \cdot 2H_2O$, or true brushite; the other analyses evidently indicate partial dehydration and are compared to metabrushite which Frondel has shown is merely a mixture of brushite and monetite.

The most interesting mineral from the Grotte de Minerve is the white plastic material first found as a vein 50 to 80 cm. thick at a depth of 3.50 meters not far from the entrance. This material was termed minervite by Gautier, but is now known (Bannister and Hutchinson, 1947) to be identical with taranakite (p. 479). Gautier at first did not determine alkalis in any of his analyses and therefore did not realize that the mineral is a hydrated potassium aluminum phosphate. The analyses given in table 50 are by Carnot (1896), and by Gautier (1914) in a later paper, based on material taken much farther into the cave. The nature and interest of this material will be more apparent when it is considered in relation to other occurrences of similar or identical minerals.

The following occurrence is probably referable to a more remote period than that just described.

BEDUER

Delfortrie (1871) has described a fissure in the surface of a plateau, at an altitude of 350 meters, in the Jurassic at Beduer, in the arrondissement of Figeau, department of Lot. The fissure is said to have been 8 meters wide, 9.8 meters deep, and at least 30 meters long. The exact arrangement of the strata relative to these dimensions is not clear. The fissure filling consisted of about 5 meters of reddish limonitic earth, in part friable, in part crystalline, with scattered granules of Fe_3O_4 . This layer contained very little phosphate, though in some parts appreciable traces were encountered. Below this was a series of strata of total thickness nearly 5 meters, of very diversified phosphorite. The phosphate was in part a cellular, friable, grayish pink, and very light rock, in part

compact, ash gray, in part dirty white, very dense and with crystalline enclosures, in part flaky, in part white, compact, but very friable. Lamellated material, some of which has onyx-like banding, also occurred. Enormous numbers of bat bones were found in the phosphorite, and Delfortrie considered, undoubtedly correctly, that the deposit represented an accumulation of bat guano and dead bats. Very few other fossils were encountered, the only other vertebrate remains being part of the humerus of a hyena, said to be identical with that of *Hyaena crocuta spelaea*, a small number of fossils of *Felis* sp., and a humerus referred to a tapir. If the last determination is correct, the deposit is presumably late Pliocene (Villafranchian). Two species of undeterminable cyclostome snails and *Planorbis* sp. were also found. The abundant remains of bats are all referred to a single new species designated *Vespertilio oltinus*. As far as can be ascertained, no further study of the material has been made. A brief description of the skull and figures of the dorsal and lateral views of the latter were given by Del-

fortrie, the condylobasal length may be somewhat less.

2. The interorbital breadth is about 4.5 to 5.0 mm. and the maximum width of the braincase 10 to 11 mm.

3. From Delfortrie's description and figure, the posterior margin of the dorsal surface of the braincase overhangs the oblique occipital region, though the exact relationships of the parts are hard to elucidate.

4. From Delfortrie's figure of the lateral view, the rostral region of the skull is as deep as the posterior region.

The characters clearly prove that *Vespertilio oltinus* cannot be equated with any living European bat.

The rather considerable number of lower Pleistocene bats described by Kormos (1934) and by Heller (1936), though known mainly from mandibles, are clearly excluded on account of their size, which in all cases was evidently less than that of "*V.*" *oltinus*. Three species of bats now living in Europe have skulls the dimensions of which approach those of the fossil (Miller, 1912).

	CONDYLOBASAL LENGTH	INTERORBITAL WIDTH	MAXIMUM WIDTH OF BRAINCASE
<i>Myotis myotis</i>	22.4-23.6 mm.	5.0-5.6 mm.	9.8-10.4 mm.
<i>Nyctalus siculus</i> (Mina-Palumbo)	22.2-22.8	5.6-6.0	11.2-11.6
<i>Nyctinomus teniotis</i>	23.0-23.8	4.8-5.0	11.2-11.6

fortrie, but no measurements were presented. The figures of the skull are, however, said to be of natural size. Recently Prof. George A. Kubler of the Department of the History of Art of Yale University reexamined the material and took small photographs under somewhat unfavorable conditions. These photographs are not suitable for reproduction but have been invaluable in examining the problem presented by the deposit. The material apparently comprises at least seven crania with some teeth and limb bones. The crania are now all attached by their ventral surfaces to cards and no information relative to palatal or dental anatomy can be obtained without their removal and further development. It is clear from Delfortrie's drawing and from Professor Kubler's measurements and photographs that:

1. The skull is very large, with an over-all length of at least 25 mm., though, owing to the apparent obliquity of the occipital

Both *M. myotis* and *N. siculus* probably differ from the fossil in their proportionately wider interorbital regions, and more strikingly in having rostra that gradually decrease in depth anteriorly. *Nyctinomus teniotis* resembles the fossil in the general proportions of the skull and in the flat dorsal profile, with a deep rostrum. It differs from the fossil, as do the other two species also, in its far less oblique occipital region. It is, however, not entirely clear from Delfortrie's figure that the skull illustrated is not damaged in the occipital region, and an affinity with *Nyctinomus* cannot be excluded on the basis of the available information.

It is at any rate reasonably certain that the Beduer phosphate was formed from the guano deposited by an extinct species of large social bat, though until the interesting remains of that bat are critically reexamined, it cannot be correctly assigned to a genus or even to a family.

THE IBERIAN PENINSULA

Bat guano is apparently found in caves throughout the Iberian Peninsula. The first record is probably that of Eschwege (1833) who observed, in a limestone cave near the fort of Marraó close to the Spanish border, a locality that has not been identified, a deposit of bat dung over 8 feet deep. Later a fair amount of Spanish guano was apparently exported. The most complete data on its occurrence are provided by the notes of Breuil, Jeannel, Racovitza, and others in the series of papers entitled "Biospéologica, Enumération des grottes visitées" (Jeannel and Racovitza, 1907, 1908, 1910, 1912, 1914, 1918, 1929). The following summary derived from these sources indicates the prevalence of guano in the caves of Spain:

	TOTAL NUMBER OF CAVES	CAVES WITH GUANO
Pyrenean provinces		
Gerona	2	0
Lerida	19	4
Huesca	27	2
Navarra	7	2
Guipúzcoa	15	6
	70	13 (18.6%)
Northern and central Spain exclusive of Pyrenees		
Barcelona	8	1
Soria	7	2
Burgos	5	1
Vizcaya	8	1
Santander	10	8
Oviedo	14	5
Leon	1	0
Castellón de la Plana	5	1
Madrid	1	1
	76	22 (28.9%)
Southern Spain and equivalent latitudes in Portugal		
Valencia	16	5
Ciudad Real	1	1
Alicante	15	7
Murcia	1	1
Granada	3	0
Málaga	13	11
Cádiz and Gibraltar	8	3
Portugal	6	4
	63	32 (50.8%)

It is clear that the regional differences indicated by these figures are in part altitudinal. Twenty-five caves are included in the Pyrenean list that are at altitudes in excess of 1000 meters. In none of these caves is guano recorded, and, if these caves be omitted, the mean percentage value for the Pyrenean provinces becomes 29.0%, which is comparable with that for the rest of the north of Spain. The general relation of the occurrence of discrete guano deposits to altitude in the Spanish Pyrenees is indicated in the histogram of figure 89. The highest locality on the Spanish side of the Pyrenees in which guano is actually recorded is the Cueva de abaho del Collorada or de las Guixas, at about 1000 meters at the base of Peña Collorada, on the left bank of the Aragon, 2 kilometers north of Villanua in the partido of Jaca, Huesca. It is a complex cave at three levels with a number of entrances. The floor of a gallery at the uppermost level on the left of the cave is said to have been covered with vegetable detritus, powdery clay, and bat guano. *Myotis* and unusually closely aggregated *Rhinolophus* are said to have been present. Mammalian bones occurred abundantly in the clay of the floor of the middle level. It is, however, to be noted that the highest caves such as the Esplluga de Las Tosas, Bonansa, partido of Benabarre, Huesca, may contain sparse scattered bat droppings. Apart from the altitudinal variation, there would appear to be a greater probability that a cave in southern Spain would contain a deposit rather than one in northern or central Spain.

There seems to be little doubt that the majority of the guano deposits of the Iberian Peninsula have been produced by *Myotis myotis*. Cabrera (1914) does not recognize *M. oxygnathus*, though this species is recorded by Falcoz (1923) as occurring with *M. myotis* in the Gruta de la Algareta, Huesca, and by itself in the Cova dels Muricets, Lerida. It is probable from Cabrera's account that, if the two species are valid, they occur together in other localities in Spain. Cabrera indicated that *M. myotis* occurs throughout Spain and Portugal, by day and in winter usually occupying natural caves, particularly those near rivers or the sea. It forms large colonies which may also contain a few *Miniopterus* and at times *Rhinolophus*.

While most of the guano deposits recorded by Breuil and by Jeannel and Racovitza are merely indicated without detail and are presumably small, the following caves appear to have contained notable quantities, deserving individual mention.

GUIPÚZCOA

Cueva de Oriamendi, Hernani, partido of San Sebastian, altitude *ca.* 30 meters. A cave about 110 meters long, in one gallery of which bats are numerous and guano locally abundant

LERIDA

Cova dels Muricets, left bank of the Noguera-Pallaresa, Llimiana, partido of Tremp, altitude *ca.* 359 meters. Evidently an important bat cave known to harbor *Myotis oxygnathus*, and with the floor covered with guano

Cova negra de Tragó, left bank of the Noguera Ribargozana, Canellas, Tragó de Noguera, partido of Balaguer, altitude 494 meters. Numerous bats frequent the cave, but the large old banks of guano which have been exploited are not in the process of reformation

Cova del Tabaco, Monroig, Camarasa, partido of Balaguer, altitude *ca.* 605 meters. Numerous bats inhabit this very dry cave which has been exploited for guano

TARRAGONA

Cova den Rubí, Tortosa, altitude 360 meters. Many bats and abundant guano in the middle region of the cave which is 150 meters long

ALICANTE

Cueva de la Punta de Beninaquia, Denia, altitude *ca.* 70 meters. Bats very numerous and guano abundant

MÁLAGA

Cueva del Churreron, Ronda, altitude *ca.* 700 meters. A cave not more than 150 meters long with very numerous bats and abundant old and fresh guano

CADIZ

Cueva del Argar, between Vejer and Casas Viejas, 20 kilometers northeast of Vejer, Vejer de la Frontera, partido of Chiclana de la Frontera, altitude *ca.* 300 meters. An old quarry, the floor being covered with fairly abundant guano containing the bodies of bats and of other animals that have fallen through holes in the roof

Large cave, Berrueco, Ubrique, partido of Grazalema. A large cave probably about 85 meters long, with numerous bats and much guano

Analyses of bat guano from unspecified caves in the south of Spain have been published by Voelcker (1878a). The material is described as dark in color and as containing

numerous insect remains. The following data were obtained:

H ₂ O				
(moisture)	33.68%	15.82%	18.81%	18.32%
Organic and ammonia	25.16	65.08	42.09	53.47
Total N	3.36	8.67*	4.96*	8.91
N·NO ₃	—	—	—	1.57
P ₂ O ₅	3.44	1.53	4.65	5.41 ^b
CaO	—	—	5.18	3.52
Alkali salts	—	13.37	—	} 2.06
Indet.	—	—	15.28	
Insol. SiO ₂	32.5	2.39	13.99	11.15

* Nitrate nitrogen not determined.

^b P₂O₅ soluble in water 1.08.

The first sample is said to have contained 1.18% "sulphate of lime, etc."

ISLANDS IN THE WESTERN MEDITERRANEAN

The Cuevas del Drach, at Porto Cristo, 12 kilometers from Manacor in Mallorca, possessed guano deposits produced by a bat colony which disappeared prior to 1904 when the cave suffered amelioration for the benefit of tourists (Jeannel and Racovitza, 1907). The Grotte de Pietralbello or de Ponte Leccia, Morosoglio, Corsica, is said by Jeannel and Racovitza (1908) to have had scattered droppings or thin guano throughout, with a thicker layer at the end of the cave.

In contrast to the rather limited occurrence of bat guano in the Balearic Islands and in Corsica, large deposits have been found in Sardinia. The earliest account of such material seems to be that of Selmi and Missaghi (1855) who state that deposits which occasionally contained up to 20,000 or 50,000 quintals (i.e., 4000 to 10,000 tons) had been found and that the depth of the guano in such immense deposits might reach 5 or 6 meters.

Binaghi (1909) indicates that the guano caves are grouped roughly in the northern and southern parts of the island. The northern group may first be considered.

GROTTA DELL' INFERNO

Said by Binaghi to be in the vicinity of Sassari, examined by Selmi and Missaghi. The guano, which was in part loose, in part agglomerated, was damp and brown in color, containing shining black particles identified

as the remains of insects, and white spots said to have consisted of clay, calcium carbonate, iron oxide, and ammonium salts. Their analysis, which is rather obscure, indicates 51.76% organic and volatile matter, 13.60% sand, and 8.25% total nitrogen.

GROTTA DE SEDINI

About 25 kilometers northeast of Sassari, also examined by Selmi and Missaghi, containing a drier, browner guano than that of the preceding locality. It contained the black inclusions derived from insects but lacked the white spots. Their analysis indicates 26.43% organic and volatile matter and 49.42% sand.

GROTTA DI BORUTTA

A cave 120 meters deep, formed of two principal galleries, evidently containing an important deposit. The guano was examined by Selmi and Missaghi, who say it was similar to that from the Grotta dell' Inferno, but more aggregated, with more insect remains, and fewer white spots. They give an analysis indicating 69.02% organic and volatile matter, 6.50% sand, and 9.22% total nitrogen. A later analysis by Ziravello (1892-1893) gave:

Ignitable matter	15.97%
N total	2.31
N·NH ₃	0.17
N·NO ₃	1.54
Insol. ash	58.41
P ₂ O ₅	5.81
K ₂ O	0.28

The deposit evidently varied greatly in quality. Giua (1919) noted considerable variation in its appearance and phosphate content. Below 1 or 2 meters at the sides of the cave he observed small beds and veins of a white material which proved to be largely calcium phosphate. He gives the following determinations:

	H ₂ O	N	P ₂ O ₅
Clayey, fairly diffuse	33.5%	1.03%	0.98%
Reddish, rather clayey	24.7	1.84	9.89
Reddish, rich in calcium carbonate	28.2	1.87	13.63
Reddish, rich in calcium carbonate	22.5	2.36	13.05
Clayey	25.6	1.42	1.79
Brownish, from surface	—	1.86	9.66

Brownish, from surface	—	—	7.04
Reddish, rich in calcium carbonate	—	1.95	12.86
Reddish, rich in calcium carbonate	28.75	—	19.84
Reddish, rich in calcium carbonate	—	—	5.82
Reddish, rich in calcium carbonate	—	—	10.75

The white phosphatic material contained:

H ₂ O	7.00%
CaO	45.57
(Al,Fe) ₂ O ₃ , etc.	4.07
P ₂ O ₅	35.05
CO ₂	3.17
SiO ₂	5.14

MONTEMAGGIORE

Near Sassari, perhaps the locality mentioned by Lamarmora (1860) as having a large cave yielding bat and pigeon guano, said by Ziravello (1892) to have contained material giving on analysis:

Ignitable material	53.92%
Total N	5.76
N·NH ₃	0.44
N·NO ₃	0.60
Insol. ash	21.37
P ₂ O ₅	2.98
K ₂ O	0.42

ALGHERO AND BOSA

A number of analyses of guano from near Alghero on the west coast of Sardinia have been collected together by Paris (1899). These are all fairly nitrogenous, the total N varying from 2.23% to 8.61% and the P₂O₅ from 2.52% to 9.98%. A guano from Bosa, analyzed by Scarafia whose figures are quoted by Binaghi (1909), contained 4.76% N and 1.06% P₂O₅.

SINISCOLA

Binaghi quotes from Sanna the following analysis of material from this locality on the northern part of the east coast of Sardinia:

Moisture	9.46%
Organic matter	39.21
N total	8.45
N·NH ₃	0.24
P ₂ O ₅ total	4.76
P ₂ O ₅ sol.	0.15
CaO	29.73
K ₂ O	2.37

TABLE 51

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII
H ₂ O at 100° C.	25.38	14.80	6.20	10.04	7.38	15.22	23.86	25.36	12.10	21.50	9.50	19.50	19.22	10.18	6.56	9.38	19.80
Ignitable	44.39	37.56	18.92	33.48	23.67	8.91	15.88	5.55	30.31	39.55	25.58	46.27	11.84	17.61	11.12	38.86	34.56
Total N	7.03	2.13	0.44	3.49	0.96	0.98	3.63	2.48	3.40	7.14	1.12	1.23	2.39	2.34	1.15	2.81	5.78
N·NH ₃ free	0.07	tr.	tr.	tr.	tr.	tr.	0.09	0.06	tr.	0.05	tr.	tr.	0.07	0.07	0.05	tr.	0.14
N·NH ₃ comb.	0.35	tr.	tr.	tr.	tr.	tr.	0.15	0.13	0.12	0.07	tr.	tr.	0.06	0.05	0.06	0.06	0.06
N·NO ₂	1.93	0.78	0.34	0.96	0.63	0.41	1.57	1.15	1.89	1.37	0.12	0.49	1.64	1.40	1.67	1.21	3.91
N·uric	4.42	—	—	1.87	—	—	1.37	0.89	0.73	4.45	—	—	0.17	0.34	—	—	0.89
Fe ₂ O ₃	0.53	0.79	4.65	7.16	0.95	1.70	1.74	1.05	0.96	0.83	1.16	1.69	5.56	3.24	5.70	3.10	1.78
Al ₂ O ₃	2.14	1.54	9.18	0.64	4.28	6.12	2.13	2.45	8.34	2.20	4.17	2.74	11.07	5.16	8.96	4.26	8.05
MgO	1.32	2.50	6.83	3.08	8.21	11.89	5.24	3.23	3.15	2.13	3.41	1.65	3.75	3.41	3.83	1.13	3.13
CaO	7.12	8.15	13.56	8.13	10.08	6.19	7.63	7.60	11.20	9.31	18.34	8.76	16.68	18.24	12.00	14.20	13.10
K ₂ O	0.71	0.74	0.96	0.78	0.73	0.47	1.16	1.93	0.76	0.78	1.03	0.84	0.83	0.63	0.72	0.57	1.05
Na ₂ O	0.87	1.25	1.27	1.07	1.24	0.84	1.07	1.76	1.23	1.03	1.54	0.93	0.65	0.74	0.47	0.37	0.84
P ₂ O ₅ total	3.41	4.16	7.16	4.40	7.42	5.62	8.07	8.15	7.16	4.23	7.65	4.12	6.35	7.10	8.73	4.74	3.47
Water sol.	tr.	0.11	0.07	0.08	0.18	0.11	0.10	0.13	0.17	0.09	0.12	0.03	0.04	tr.	0.10	0.04	0.13
Citrate sol.	1.53	2.06	2.84	1.32	2.02	1.58	1.92	3.10	5.06	1.98	2.61	1.12	2.14	2.72	3.20	1.37	1.41
SO ₄	1.57	3.65	4.35	7.18	8.27	6.93	9.14	8.54	4.47	4.14	2.27	2.86	3.40	8.17	13.29	4.61	3.38
Cl	2.32	2.63	2.15	3.27	2.54	1.74	2.64	2.25	0.89	1.83	3.90	3.10	0.40	2.52	0.35	0.24	2.30
CO ₂	3.25	1.93	9.47	2.79	5.31	1.53	2.95	4.05	1.64	5.23	3.84	1.97	10.13	12.90	11.37	4.17	4.57
SiO ₂ and insol.	6.03	19.16	12.83	20.33	18.20	31.63	16.33	25.83	17.30	7.27	16.37	4.73	9.37	9.74	25.86	13.46	3.27

I. Grotta Boe Marinu, Dorgoli, superficial, almost black, smelling of urine.

II. Same, deep red brown, not unpleasant odor, insect remains.

III, IV. Same, lighter, small calcareous inclusions.

V, VI. Still lighter and more calcareous.

VII. Grotta Biddiscottai, top.

VIII. Same, middle.

IX. Same, bottom.

X. Grotta Coazza, Dorgoli, superficial.

XI. Grotta N, Dorgoli, superficial.

XII. Same, deep.

XIII. Grotta Gologone, Oliena, black with calcareous fragments.

XIV. Same, lighter.

XV. Same, hazel brown.

XVI. Same, tobacco colored.

XVII. Grotta Conca Ruia, Orosei, mixed sample.

CAVES NEAR OLIENA, DORGOLI, AND OROSEI

Somewhat south of the preceding and said to be large and with considerable deposits, have yielded guano studied by de Dominicis (1919). Very little stratigraphic or other information relative to the occurrences is given; the largest deposit is that of the Grotta Biddiriscottai, in which up to 1000 tons of guano are supposed to have been present. The full analyses are given in table 51.

TISSI AND SCALA DI GIOCA

Recorded by Binaghi without details, as northern Sardinian localities yielding cave guano.

The following localities are in the southern half of Sardinia:

IGLESIAS

Binaghi quotes from Sanna the following three analyses from the region of Iglesias, in the southwest of Sardinia:

Moisture	10.60%	16.80%	10.41%
Organic matter	37.72	47.06	49.44
N total	2.08	5.06	4.03
N·NH ₃	0.94	0.13	0.11
P ₂ O ₅ total	8.63	10.24	2.38
P ₂ O ₅ sol.	2.76	4.03	2.05
CaO	7.35	17.16	8.84
K ₂ O	1.97	3.17	1.76

CARLOFORTE

On the island of San Pietro off the southwest corner of Sardinia, yielded two samples to Sanna, whose analyses are quoted by Binaghi:

Moisture	19.73%	24.38%
Organic matter	51.64	43.82
N total	5.42	6.24
N·NH ₃	0.96	2.07
P ₂ O ₅ total	14.50	12.57
P ₂ O ₅ sol.	9.41	6.38
CaO	8.37	12.71
K ₂ O	0.42	0.84

DOMUSNOVAS

A cave called Perdu Carta in the region Sa Xemesa, near Grotta de San Giovanni di Domusnovas, presumably in southwest Sardinia, examined by Binaghi. The material was exclusively derived from bat droppings and was dark in color:

Moisture	8.16%
Organic and volatile	57.92
N total	4.06
N·NH ₃	0.84
N·NO ₃	0.76
P ₂ O ₅	1.50
K ₂ O	0.12
Insol.	20.71

SANTADI

Between Iglesias and Cagliari, yielded guano analyzed by Ziravello, whose data are quoted by Binaghi:

Organic and volatile	84.40%
N total	11.74
N·NH ₃	1.65
N·NO ₃	1.87
P ₂ O ₅	3.80
Insol.	3.84

CAGLIARI

Paris (1899) gives a rather complete analysis of a bat guano from near Cagliari. The sample consisted of fecal pellets about 3 mm. long, with a fine powder the color of tobacco:

Moisture	13.85%
Organic and volatile	58.78
N total	7.82
N·NH ₃	1.09
N·NO ₃	0.17
N·uric	0.21
P ₂ O ₅	5.36
(Al,Fe) ₂ O ₃	5.20
CaO	1.72
MgO	0.48
Na ₂ O	3.10
K ₂ O	1.77
SO ₃	2.28
CO ₂	1.80
SiO ₂ , etc.	4.82

LANUSEI, GAIRO, AND OTHER LOCALITIES
IN SOUTHEAST SARDINIA

Binaghi gives several analyses of material from localities which appear to be near Lanusei, just south of the middle of the eastern coast of the island. The material from the Grotta dei Colombi is of interest as this is apparently a raised sea cave formerly inhabited by wild pigeons rather than bats. The exact position of this cave, and of Urzulei and Ierzu, has not been ascertained.

It is interesting to note that, at least as far as these analyses go, the cave guano produced

TABLE 52

	I	II	III	IV	V
Moisture	12.10%	8.38%	6.88%	18.96%	11.92%
Organic and volatile	62.66	61.18	51.02	49.45	45.02
N total	6.16	5.90	5.74	5.81	4.76
N·NH ₃	2.80	3.33	1.40	3.08	0.60
N·NO ₃	1.76	0.99	1.24	0.89	0.78
P ₂ O ₅	2.84	1.31	0.93	0.54	0.79
K ₂ O	0.21	0.60	0.58	0.34	0.36
Insol.	22.72	16.90	31.61	11.21	10.50

- I. Lanusei, brown earthy.
 II. Grotta dei Colombi, between Capo San Elia and Sella del Diavolo, east coast of Sardinia, dark chestnut, little earthy matter, largely bird droppings.
 III. Urzulei, intense brown, rich in coleopterous remains.
 IV. Ierzu, light chestnut, virtually free from earthy matter.
 V. Gairo, light brown, earthy.

by pigeons differs little from that produced by bats.

In addition to these analyses, Binaghi indicates the occurrence of bat guano in southern Sardinia at Tortoli, Seulo, and Ulassai; at least the first two of these localities are in the vicinity of Lanusei. He also quotes the following analyses for samples from localities that have not been identified:

	I	II
Moisture	19.24%	28.24%
Organic and volatile	62.28	51.10
N total	10.07	6.67
N·NH ₃	1.42	—
P ₂ O ₅ total	2.98	3.55
P ₂ O ₅ sol.	1.56	—
CaO	12.40	—
K ₂ O	0.97	—

- I. Lula (analysis by Sanna).
 II. Bauladu (analysis by Scarafia).

All the available Sardinian analyses have been used in preparing figure 100, in which the total nitrogen is plotted against total P₂O₅. The relative richness in nitrogen of most of these samples is immediately apparent from the graph.

PENINSULAR ITALY AND SICILY

Of the 11 caves in northern Italy considered by Jeannel and Racovitza (1929), two, the Buco del Frate, Paitone, Sala, Brescia, and the Buco del Soglio, Marte di Malo, Schio, Vicenza, are said to have contained guano. The proportion is of the same

order as in southern France, but the numbers are too small to be of significance. The following analyses of Sicilian and Italian guanos have been published, but there are virtually no details as to the mode of occurrence:

	I	II	III	IV
Moisture	42.69%	18.02%	10.32%	53.08%
Organic matter	20.80	29.11	42.83	34.17
Total N	2.02	2.996	3.51	3.74
P ₂ O ₅	1.17	10.94	6.13	0.96
CaO	—	7.32	—	2.83
MgO	—	0.09	—	0.04
K ₂ O	—	1.10	—	0.144
Na ₂ O	—	0.43	—	0.11
(Al,Fe) ₂ O ₃	—	8.90	0.99	2.39
Sand, etc.	—	23.63	?	4.03

- I. Frassassi, Marche (Sestini, 1876).
 II. Eboli, Salerno, chocolate colored, rare concretions of lime, acid reaction (Paris, 1897).
 III. Sant' Agata d'Esaro, Castrovillari, Calabria (Giunti, 1881a).
 IV. Pachino, Sicily (Josa *in* Paris, 1899).

Giunti found 0.348% to 0.403% CuO in the Sant' Agata sample; Paris, only minute traces of copper and manganese in the Eboli sample.

MONTE ALBURNO, CONTRONE, SALERNO

In a vast cavern on the slope of Monte Alburno, Casoria (1904) records a notable deposit of bat guano beneath which was a white mineral containing:

H ₂ O -100° C.	7.87%
H ₂ O +100° C., etc.	21.29
Al ₂ O ₃	22.89
Fe ₂ O ₃	1.17
K ₂ O	8.04
Na ₂ O	0.02
NH ₃	0.61
P ₂ O ₅	37.10
SiO ₂	0.36

This material, which was named palmerite, is known to be identical with taranakite (Bannister and Hutchinson, 1947).

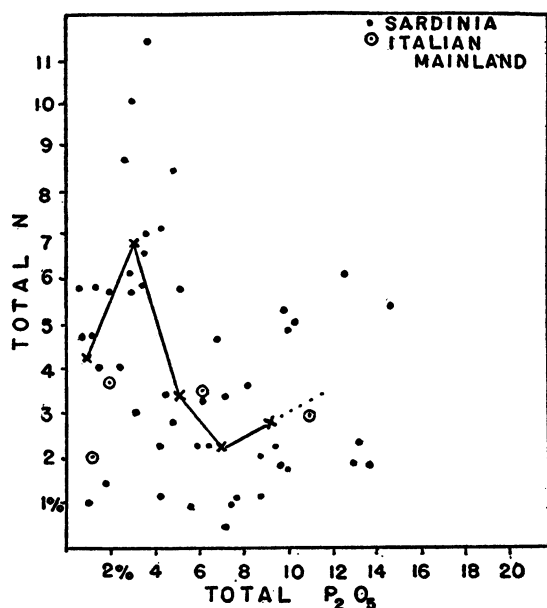


FIG. 100. Relationship of total nitrogen to phosphate in Sardinian cave guanos.

GREAT BRITAIN

In accordance with the absence of *M. myotis* from the British Isles, no extensive modern deposits of bat guano occur. Isolated heaps of droppings beneath the roosting places of the more or less solitary cave bats, such as *Rhinolophus ferrum-equinum*, are of course to be expected and have in fact been recorded, for instance at the Cheddar Caves by Coward (1907). A few fecal cave deposits of varying degrees of antiquity, not, or only in small part, due to bats have been described.

ARGYLLSHIRE, SCOTLAND

Anderson (1857) gives an analysis of material, apparently formed from the dung of the red deer, *Cervus elaphus*, which had habitu-

ally taken shelter in a shallow cave. The deposit consisted of a soft, brown, pulverulent material, almost devoid of odor and containing:

Moisture	21.63%
Organic and volatile matter	50.91
NH ₃	2.17
CaO	3.85
MgO	2.17
Na ₂ O	5.39
K ₂ O	4.65
P ₂ O ₅	1.56
CO ₂	3.94
Cl and SO ₃	5.59
Sand	0.33

CAVE HA, GIGGLESWICK, SETTLE, YORKSHIRE

This is a large, half-dome-shaped rock shelter, with a funnel-shaped cavity at the top. It was excavated by Hughes (1874), who found:

- A. 1 ft. + Surface mold with the pellets of owls, kestrels, etc.
- 2-4 ft. Earth with much vegetable matter comprising old floors with charred wood, modern and ancient pottery, antique knives, an ox shoe, a stone bead, flint flakes, and bones. The whole much disturbed by mouse burrows, and with a large number of mouse bones *in situ*
- B. Up to 2 ft. Decomposed powdery travertine and limestone; fragments of limestone, in part cemented to form a breccia; mouse bones crowded into the interstices of some portions, but few other bones
- C. Yellow clayey sand and clay
- D. Carboniferous limestone (bedrock)

The layers designated A contained ox, sheep, goat, deer, pig, badger, hare, rabbit, mouse, fox, and dog bones, perhaps those of wild goose, of a small species of duck, and the otolith of a fish. The layers designated B contained, as well as mouse bones, those of ox, goat, and sheep, and one molar of a bear. A large part of the A layers is obviously quite modern. Marr (1876) found that a considerable amount of the cave filling was phosphatized. The phosphatic material formed friable, leaden gray stalagmitic layers at the sides of, and interstratified with, the main deposit, and in parts contained a large percentage of calcium phosphate. The level of

its occurrence is not quite clear from Marr's account, but at least part was evidently in the travertine layer at the top of B. Marr supposes that the phosphate was derived from the leaching of owl and kestrel pellets, though some phosphate would also obviously be derived from the excreta of these birds.

KENTS CAVERN, TORQUAY, DEVON

There seems to have been some phosphatization in this cavern, though the phosphate was in general doubtless present mainly as hyena feces, as is indicated below (Mac Enery, 1869). Barrett-Hamilton (1911), commenting on the discovery of fossilized bones of *Rhinolophus ferrum-equinum* in this cave (Owen, 1846) indicates that the droppings of these bats had been collecting in the cave for an immense period. He gives no authority for the statement and the available accounts of the cave filling make no specific mention of bat guano.

NOTE ON ALBUM GRAECUM OR THE FOS- SILIZED DUNG OF THE CAVE HYENA, *Hyaena crocuta spelaea*

In 1821 Buckland (1822, 1823) discovered in a recently opened cave at Kirkdale, Yorkshire, England, a number of specimens which he described as "resembling the substance known in the old materia medica by the name of album graecum." These specimens were associated with many bones of hyenas and other Pleistocene mammals. They are described as being spherical, irregularly compressed, half an inch to one and a half inches in diameter, earthy, compact, yellowish white in color, and sometimes containing undigested minute fragments of tooth enamel. Buckland realized that these were the fossilized feces of an animal that had fed on bones, and the objects were recognized by "the keeper of the menagerie at Exeter Change" as resembling the droppings of "the spotted or Cape Hyaena, which he stated to be greedy of bones beyond all other beasts under his care."¹ Wollaston, a leading British

chemist of the day, examined the album graecum specimens chemically and reported that they consisted of "phosphate of lime, carbonate of lime, and a very small proportion of the triple phosphate of ammonia and magnesia."

It is difficult to ascertain how often this fossilized hyena dung formed a definite phosphatic deposit and how often it was merely distributed as isolated coprolites in otherwise unphosphatized cave earth. Great quantities were certainly found in Kent's Cavern (Mac Enery, 1869).²

In the hyena den at Wookey Hole, Somerset, quantities of broken bones and hyena coprolites were found, the latter forming in some places a grayish white layer of phosphate of lime. Black lines, attributed to manganese, are associated with these deposits, as at the Drachenhöhle. The same material formed irregular floors in the cave earth of the Victoria Cave, Settle, Yorkshire (Dawkins, 1874).

On the continent fossil hyena feces were figured by Croizet and Jobert (1828) but not from cave deposits. The most notable account of the occurrence of a definite stratum of hyena feces is in the Grotte du Prince, one of the Grottes de Grimaldi at Baoussé-Roussé, on the Mediterranean coast at the French-Italian frontier. At this celebrated site, Boule (1906) found two definite layers of hyena droppings in stratum 3, which lies between two human occupation levels. Evidently here hyenas occupied the cave when it was deserted by paleolithic man, and man again entered when hyenas had gone. These events occurred during the last interglacial (Zeuner, 1945).

The discovery of hyena feces and gnawed bones, showing that the Kirkdale cave was in fact a hyena den, introduced an ecological point of view into paleontology which was of considerable intellectual significance in making the scientific public aware of the importance of cave deposits. It is interesting to note that in the copy of the "Reliquiae diluvianae" consulted, which was presented by Buckland to Benjamin Silliman, the passages about album graecum are among the very few marked with marginal pencil lines.

² The writer believes that when a boy, 30 years ago, he saw specimens from Welsh caves in the paleontological cabinet of Dr. Lloyd Jones of Cambridge, England. Examination of the literature of the Welsh bone caves indicates records of hyena dens but no indication of fossil feces. It is, however, possible that the specimens in question came from one of the caves in the west of England and not from Wales.

¹ Buckland quotes later in the "Reliquiae diluvianae" accounts of hyenas in captivity gnawing off their own feet. This, and the remarks about their greediness for bones, rather suggest an excessively inefficient absorption or utilization of dietary calcium, as in the opossum. This matter is commended to the attention of such comparative physiologists who may chance on this note.

GENERAL ASPECTS OF CAVE GUANO

The detailed presentation of the data relating to cave guano shows that there are likely to be deposits in any parts of the temperate or tropical regions in which caves are developed and which are inhabited by highly social bats. As in the case of avian guano deposits, the greatest accumulations appear to have formed during the interglacial episodes of the Pleistocene, but there is no reason to believe that the deposition of chiropterite during the Riss-Würm interglacial is in any way connected with changes in terrestrial productivity or in the general cycle of the elements. All that seems to be required to produce chiropterite is a suitable cave, sufficient social bats, and sufficient time. Though little general chronological information can be obtained from the studies of bat caves, the detailed results of the exploration of such a cave as the Drachenhöhle is of course of the greatest interest, and it is regrettable how rarely such exploration has been attempted elsewhere. The conclusions from such studies are less grandiose than such as can be drawn from the insular deposits, but they admittedly have a certain fascination in themselves and are of considerable importance in local geochronology and archaeology.

Apart from such problems, there is a certain number of geochemical questions raised by the deposits of bat guano. Some are best

considered in conjunction with the comparable problems raised by the bird islands; three of these special questions may, however, be conveniently considered here.

THE RELATIONSHIP OF NITROGEN TO PHOSPHORUS

The analysis of the droppings of *Rhinolophus ferrum-equinum* given by Popp (1871) indicates 8.25% N and 2.25% P, corresponding to a molecular N:P ratio of 8.12. Any sample containing less of both constituents simultaneously is likely to be contaminated with extraneous material. There is, however, obviously variation in the ratio even in fresh samples. In the two fresh Puerto Rican samples compared on page 381 with Popp's specimen, the nitrogen is higher, but the phosphorus is proportionately even greater, so that the ratios are 3.28 and 3.51. The quantity of urine incorporated in the deposit would certainly be important in determining this ratio, but it is difficult to know in what direction. When the nitrogen is plotted against the P_2O_5 content, the mean curves for most regions show a certain similarity. There are, however, divergences from the general pattern. It is in fact possible to give a rough classification of the mean curves, as presented in figure 101, into three categories:

1. Marked maximum nitrogen content in

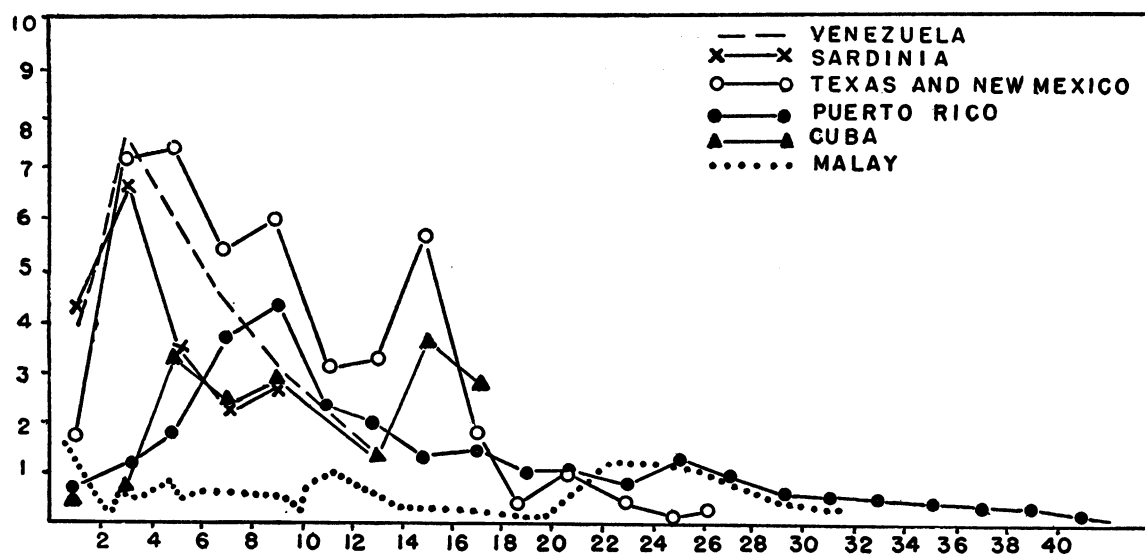


FIG. 101. Geographical variation of relationship of total nitrogen to phosphate (see text).

the lower part of the phosphate range, from 2% to 4% P_2O_5 as in fresh guano. These curves evidently represent the decomposition of organic matter with a concurrent loss of nitrogen. They are derived from both temperate (central Europe, Sardinia) and tropical regions (Venezuela, Philippines). The Texas and New Mexico curve possibly suggests a transition to the next type.

2. In Cuba and Puerto Rico, a low nitrogen

THE DECOMPOSITION OF NITROGEN COMPOUNDS

The only adequate data relate to Puerto Rico (fig. 102). It is evident that in the most nitrogenous material, 10% or more of the nitrogen is always present as either ammonia or nitrate, and that usually considerably less than 90% is organic. Nitrate is usually, but not invariably, in excess of ammonia. The maximum ammonia in any total nitrogen

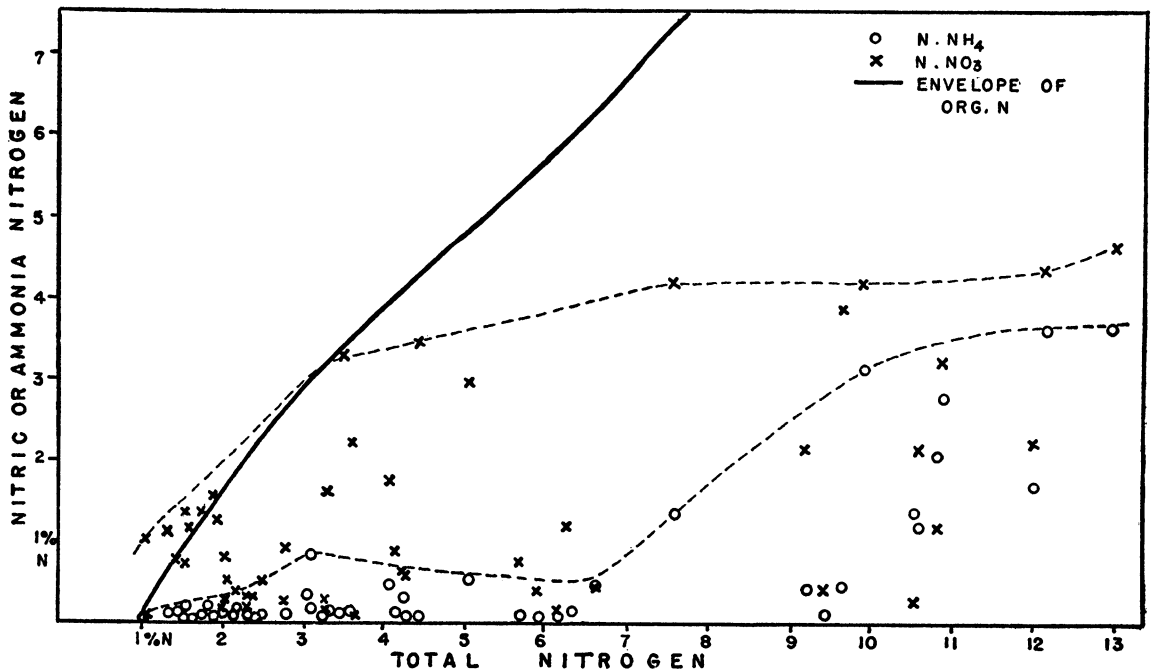


FIG. 102. Relationship of nitrate nitrogen and ammonia nitrogen to total nitrogen in Puerto Rican guanos.

maximum corresponds to a range in phosphate contents from 4% to 10% P_2O_5 . In such regions there is clearly a tendency towards enrichment of nitrogen relative to phosphorus as decomposition occurs. This is probably characteristic of areas with caves just damp enough and warm enough to permit reasonably rapid decomposition, but not wet enough for the inorganic nitrogen products to be leached as fast as they are formed.

3. In Malay, decomposition and loss of nitrogen evidently proceed fast enough for the main form of the curve to be determined by the dilution of phosphate by extraneous matter.

category falls far more rapidly with declining total nitrogen than does the maximum nitrate. In the range from 3% to 7% total nitrogen, it can all be present as organic, which is never the case above 7% N. In the lower part of the range nitrate predominates very clearly, not only over ammonia, but also over organic nitrogen in many cases. The last trace of nitrogen to remain as diagenesis proceeds would appear to be invariably mainly nitrate. Although no bacteriological investigations have been made, the most reasonable explanation of the observed facts is that initially both stable organic nitrogen in chitin and arthropodin and relatively un-

stable organic compounds, such as urea, and inorganic compounds, such as ammonia, are present. The ammonia content will depend on the rate of utilization of ammonia as a source of nitrogen by bacteria, the rate of ammonification as the stable compounds are attacked, the rate of nitrification, and the rate of loss by diffusion or leaching. Nitrification clearly proceeds fast enough for a fair amount of nitrate often to be present. As the less stable organic compounds are removed, ammonification can only occur slowly, and the ratio of nitrate to ammonia tends to increase. Meanwhile denitrification is likely to be slowed, as it depends on a supply of relatively easily metabolized organic matter, being in fact a substitute for aerobic respiration in the metabolism of such organic matter. At the end of the process, when little nitrogen is left, the processes leading to nitrate formation apparently continue, but denitrification becomes less and less important as the supply of oxidizable organic matter becomes exhausted. At every stage in the process save the final one, the stationary concentrations depend on so complex a balance that a very great variety of results may be expected. Only at the end, when practically no organic matter is present, will any uniformity be achieved, and here all processes, insofar as they do not lead to loss from the deposit, will lead inevitably to the accumulation of nitrate.

THE COPPER CONTENTS OF BAT GUANOS

The most curious chemical character re-

corded of bat guanos is the copper content of some of them. Giunti (1881b) recorded from 0.348% to 0.403% CuO in the guano of Sant' Agata d'Esaro, Castrovillari, Calabria. These results were criticized by Karwowsky (1881) who could not duplicate them on a sample of bat droppings, presumably from Russia. Paris (1897) found only minute traces of copper in his sample from Eboli. In spite of the fact that Giunti certainly got evidence of copper in his guano but not in the limestone of the roof and floor of the cave in which it occurred, it would have seemed reasonable to dismiss his results as due to contamination during analysis, if it were not for the high copper contents of certain Malayan guanos. In these Dunstan (1905) recorded from 0.34% to 0.37% CuO, figures of the same order of magnitude as those given by Giunti for his sample. It is evident that any copper that occurred in the insects that the bats eat would appear in the deposit, and that owing to the metabolic loss of most of the carbon of the food, this and other metals would be enriched in the guano. The quantities noted by Giunti and Dunstan seem, however, to be excessive; the matter evidently requires further investigation.¹

¹ R. Kettner (1948, *Sbornik Stát. Geol. Ustavu Českoslov. Rep.*, vol. 15, pp. 41-64, *abstract in Chem. Abstr.*, 1950, vol. 44, p. 86) gives an elaborate account of erosion by bat-guano solutions in caves at Domice, Czechoslovakia. Phosphate is found to migrate farther than sulphate which is precipitated as gypsum close to the guano.

THE COMPARATIVE GEOCHEMISTRY OF GUANO MINERALS

THE TWO MAJOR TYPES OF DEPOSIT, the excreta of fish-eating birds that have accumulated on islands and those of insect-eating bats that have accumulated in caves, differ considerably in their initial composition. Fresh avian guano consists largely of uric acid, while fresh bat excreta consist largely of undigested hexapodan skeletons, composed of chitin and arthropodin, presumably with a considerable amount of urea derived from the urine. One curious case of the occurrence of urea practically as a crystalline mineral in a cave in Egypt has been reported. Both avian and chiropteran deposits will contain sulphate and phosphate, alkalis and alkaline earths. The final fate of the two different kinds of guano is to decompose, leaving an insoluble residue largely composed of calcium phosphate, but in the process crystalline minerals may be formed by the evaporation of solutions that have passed through the guano, or by the interaction of substances in such solutions with the inorganic material of the environment. It has seemed desirable to collect together the information already given in the body of the text relating to these processes, so that the determinants, whether they are the nature of the original material or the physical and climatic nature of the environment, controlling possible alternative diagenetic routes, may become more apparent.

Before the well-defined substances formed in part or wholly from guano are considered, it is desirable to call attention to two problems relating to complex organic materials that occur in some specimens. The first of these problems is that of the nature of the dark red humic coloring matter found in the ancient guano, the guano colorado of the Chilean deposits. Presumably the pigments

of the old Chincha deposits were similar. The Chilean material is still available and should prove interesting. The second problem relates to the nature of the very highly nitrogenous substances that are sometimes formed in guano deposits. Wetzel (1930) found that the organic matter of the inland Chilean guano of Gruetas, Pampa del Toco, contained 16.2% N; much of this material was soluble in ammonia, giving a red solution of a humus-like substance. The residue, consisting of a chitin-like material (I), contained just over 20% N. This represents a great enrichment over the nitrogen content (6.4%) of true chitin, and a lesser but probably significant enrichment over the nitrogen content of the chitin and pseudokeratin (arthropodin) mixture, likely to be present. The carbon content is curiously low, and the molecular C:N ratio is 2.23:1. A comparable nitrogen content is recorded in the case of the organic matter of one specimen of scharizerite (II) that occurred in part of the chiropterite deposit of the Drachenhöhle at Mixnitz. The two substances, however, differ greatly in carbon, and presumably in oxygen, content.

	I	II
C	38.4%	54.69%
H	5.7	3.09
N	20.1	20.85

Though it is quite likely that the enrichment of these two substances involved entirely different processes, they are certainly of interest, and further work, if only to identify degradation products, might be significant if the materials are available. It is also possible that the supposed persistence of purine bases in highly decomposed guano would provide an interesting problem.

WATER-SOLUBLE MINERALS

OXALATES

The oxalates are the most characteristic minerals of nitrogenous guano. It is evident from the fact that insoluble as well as water-soluble oxalate occurred in old Peruvian guano that calcium oxalate was distributed

throughout the material, but it is not known in what form it occurred. Shepard's record of whewellite is most unlikely to be well founded, though the mineral is inherently a probable constituent. The well-established oxalate of the Peruvian guano is oxammite,

$(\text{NH}_4 \cdot \text{OOC})_2 \cdot \text{H}_2\text{O}$, identical with the ordinary synthetic salt, in spite of earlier statements to the contrary. This evidently occurred in quantity at Guañape and is known to have replaced birds' eggs. The evidence for the occurrence of complex sulph-oxalates is entirely inadequate. Since the oxalic acid of Peruvian guano was formed by the bacterial decomposition of uric acid, the chief constituent of the fresh bird droppings but not likely to occur in quantity in any cave deposit, the absence of oxalates from cave guano is entirely comprehensible.

SULPHATES

Taylorite, a potassium ammonium sulphate $(\text{K}, \text{NH}_4)_2\text{SO}_4$, in which potassium predominated, was evidently as common a mineral in the Peruvian deposits as was oxammite. A similar mineral occurred at Ichabo. The pure end members, arcanite, K_2SO_4 , and mascagnite, $(\text{NH}_4)_2\text{SO}_4$, may also have occurred. The identification of the latter is probable, that of the former very dubious. In several cases a potassium ammonium sulphate occurred with oxalate replacing birds' eggs, and the name guanapite was introduced by Shepard for a similar potassium ammonium sulphate containing oxalate occurring in Guañape guano. There is absolutely no evidence that these supposed minerals are not mechanical mixtures. Shepard's guanoxalite, $\text{K}_2\text{SO}_4 \cdot (\text{NH}_4)_2\text{C}_2\text{O}_4 \cdot 7\text{H}_2\text{O}$, is, however, curious on account of its high water content. Guanovulite, supposedly $(\text{NH}_4)_2\text{SO}_4 \cdot 2\text{K}_2\text{SO}_4 \cdot 3\text{KHSO}_4 \cdot 4\text{H}_2\text{O}$, is remarkable in being an acid sulphate, but again there is no proof of the homogeneity of the material.

While there is one record of a Cuban cave deposit which consisted largely of potassium sulphate, no analysis is available. The two adequately known occurrences of soluble sulphates associated with bat guano differ from taylorite in containing water of crystallization. It is possible that they may be related to some of the hydrated sulphates found in the pseudomorphs of eggs that have just been mentioned. The two hydrated sulphates¹ from bat guano gave on analysis:

¹ Mr. Benoit informs me just as the proof of this page is being returned that there is some doubt whether or not lecontite is really a hydrated sulphate.

	I	II
Na_2O	17.56%	—
K_2O	2.67	24.7%
$(\text{NH}_4)_2\text{O}$	12.94	11.1
SO_3	44.97	38.0
H_2O	19.45	25.0

I. Lecontite, Las Piedras, Comayagua, Honduras.

II. Réunion, Tunnel du Cormoran.

The widespread occurrence of gypsum in both deposits of insular guano and in bat caves must be noted. It is probable that on small low islands by far the greater part of this mineral is derived from sea water. In bat caves, it is quite probable that the gypsum represents the result of the interaction of sulphates of excretory origin, in more or less acid solution, with the limestone of the cave. Such solutions, evaporating after calcium had dissolved in them, would deposit gypsum before any other probable constituent except CaCO_3 .

NITRATES

As has been indicated in the discussion of the diagenetic changes in bat guano, the last fraction of the original nitrogen to remain in the guano is nearly always present as nitrate. This phenomenon is probably an example of a general tendency in the geochemistry of nitrogen. The various possible nitrogen compounds present in any damp deposit of biological origin are normally undergoing interconversion by bacterial metabolism. Denitrification depends on the existence of organic hydrogen donors; it is in fact a substitute for aerobic respiration. As the organic matter of the deposit is dissipated, the rate of denitrification presumably must decline, though oxidation of ammonia to nitrate could be used by the appropriate bacteria as an energy source. It is therefore not unexpected that, in the presence of free oxygen and in the absence of organic matter, nitrate should be the stable form of combined nitrogen in the biosphere, as might in fact be expected, though in heterogeneous biological systems not legitimately predicted from thermodynamic considerations (cf. Cooper, 1937).

Little is known about the nitrate of avian guano, save that in the more highly decomposed guanos some nitrate occurred. The sup-

posed presence of caliche or nitratite above some of the Peruvian and Chilean deposits is unsupported by analyses. The insuperable difficulty of accounting for the fate of the phosphate is, in the present writer's opinion, a fatal objection to all theories of the origin of Chilean and other nitrate deposits from guano. It is hoped to revert to the general problems of nitrogen fixation raised by such occurrences in a later contribution to this series.

Most of the cave nitrate that has been worked commercially, mainly in times of national stress, has been lixiviated from cave earth mixed with wood ashes, and so appears as KNO_3 . It is quite likely that in most limestone caves nitrocalcite, $\text{Ca}(\text{NO}_3)_2$, is the common nitrate. Gale (1912) states that this was the case in some of the Kentucky caves. Nitratite, NaNO_3 , is recorded as the chief nitrate in the incrustations, apparently derived from guano solutions, formed by an ancient bird colony on the shore of Lake Lahontan, near Lovelock, Nevada. It is possible that here the sodium came from the waters of the lake, as the colony must have occupied the site at a fairly late stage in the recession of Lake Lahontan. A good many cases of nitrate in cave earth must, however, be unequivocally referred to saltpeter or

niter, KNO_3 . The very high potassium contents of some of the New Mexican guano ashes clearly indicate enrichment of niter in the original guano. It is quite probable that, in nearly all such cases which seem associated with bat colonies in caves in collapsed lava flows and in other volcanic rocks, the potassium is of non-biological origin.

PHOSPHATES

Stercorite, $\text{NaH}(\text{NH}_4)\text{PO}_4 \cdot 4\text{H}_2\text{O}$, is the only adequately known soluble phosphate occurring as a discrete crystalline mineral in guano. It occurred at Guañape and Ichabo; since it seems probable that the sodium was of marine origin its absence from cave deposits is reasonable. Nothing is really known of the ammonium phosphates recorded by Shepard.

BICARBONATE

Teschemacherite, $(\text{NH}_4)\text{HCO}_3$, was evidently of common occurrence in the Chinchu deposits. It is probably the most unstable of the guano minerals, and little or nothing seems to survive of specimens in museum collections. The main source of the constituents of the mineral was presumably from the decomposition of uric acid, and it is an obvious and likely material to form from avian guano.

CALCIUM PHOSPHATE MINERALS

The naturally occurring (Fron del, 1943) solid members of the system $\text{CaO-P}_2\text{O}_5\text{-H}_2\text{O}$ are:

Brushite	$\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$
Monetite	CaHPO_4
Hydroxylapatite	$\text{Ca}_{10}(\text{P}_2\text{O}_8)_6(\text{OH})_2$

Of these, the last named alone is congruently soluble, both the dicalcium and tricalcium phosphates when treated with water losing more P_2O_5 than CaO (Bassett, 1917; Lorah, Tartar, and Wood, 1929). In addition to these substances, the anhydrous β -tricalcium phosphate is known as the mineral whitlockite in igneous rock, and martinite appears to be a variety of this mineral in which some CO_2 and water are present.

BRUSHITE AND MONETITE

The hydrated brushite is the low-temper-

ature modification, monetite the high-temperature modification. It is evident from the work of Kazakov (1937) that brushite is formed below 25°C . and at a hydrogen ion concentration below pH 6.4. In dry air at least, finely divided brushite decomposes spontaneously to monetite. Brushite may be expected wherever solutions containing an excess of phosphorus over that required to produce $\text{Ca}_3\text{P}_2\text{O}_8$ or hydroxylapatite evaporate, and where the mineral is exposed to air of sufficient humidity to prevent decomposition. These conditions are doubtless most commonly found in caves such as the Drachenhöhle, Csoklovina Cave, and Grotte de la Coquille associated with bat guano. The type locality is, however, Aves Island in the Venezuelan Leeward group, where the mineral occurred in druses in phosphate rock (Moore, 1865; Fron del, 1943). It also oc-

curred at Sombrero (Julien, 1867; Frondel, 1943), Navassa, and possibly at Los Monges. Frondel speaks of the mineral as not uncommon in insular phosphate, but this seems to be an exaggerated statement. It is otherwise known encrusting ancient bones in recent deposits. It is isostructural with gypsum, and the double salt ardealite is known from the Csoklovina Cave.

Monetite is known unequivocally from Monito, Los Monges, and Ascension, and may have been present as a dehydration product of brushite in Julien's metabrushite from Sombrero (Frondel, 1943). It is quite probable that monetite is much commoner in post-Pleistocene insular phosphates than has usually been supposed. The so-called crust guano of Baker, Jarvis, Malden, and Starbuck Islands usually contained considerably more P_2O_5 relative to CaO than in hydroxylapatite or even in $Ca_3P_2O_8$. As has been indicated, Liebig (1861) considered that about as much dicalcium as tricalcium phosphate was present in his Jarvis Island sample. Hague (1862) gave an analysis of a particularly pure crust guano which cannot have consisted of any known phosphate other than monetite:

	CRUST GUANO	COR- RECTED FOR GYPSUM, etc.	CAHPO ₄ RE- QUIRES
H ₂ O at 100° C.	0.12%	—	—
H ₂ O and organic	9.62	9.25%	6.6%
CaO	38.32	38.66	41.2
SO ₃	1.63	—	—
P ₂ O ₅	50.04	52.04	52.2
Indet.	0.27	—	—

This specimen, which is apparently still preserved in the Brush collection of Yale University, was evidently a thin white superficial crust. Such crusts would be formed by the evaporation of solutions enriched in phosphate that might move to the surface by capillarity. In fresh Peruvian guano, a molecular ratio of $CaO:P_2O_5=1:0.5$ is evidently not uncommon, and some of the phosphate may be water soluble, extracted no doubt as ammonium phosphate. Water drawn up through such materials would tend to remove phosphate from them, and even after all the organic matter had decomposed, the incon-

gruent solubility of the calcium phosphates would lead to an impoverished solid phase that gradually approached hydroxylapatite, and an enriched solution which would deposit brushite or monetite on evaporation at the surface. The general climatic conditions would probably insure the decomposition of any fine deposit of brushite in the crust. The crust guano at Starbuck is said by Voelcker (1876) to have contained $CaHPO_4$ and to have lain under the powdery guano or to have been mixed with the latter. Evidence of enrichment in P_2O_5 at the bottom of the deposit was also obtained by Dixon (1878b) at Malden Island. In such cases it is reasonable to suppose that the crust was formed by descending solutions which may have accumulated over coral rock rendered impervious by previous phosphatization, and evaporated *in situ* during the long rainless periods to which these islands are subject.

Crust guanos probably containing monetite also occurred on Raza Island, San Pedro Martir Island, and the Farallon de San Ignacio, in the Gulf of California. It appears probable from Krull's (1894) account that these crusts lay over old powdery material.

The most remarkable case of a crust guano is probably the "petrified guano" of Los Monges, which seems to have formed a hard layer over the island. The main constituents are known to have been monetite and an apatite; whitlockite (or martinite) certainly occurred and possibly brushite also. It seems reasonable to suppose that this deposit represented a crust guano of the kind found at Starbuck or Malden, under the original powder, which may have been washed or blown away. The existence of monetite and apatite in such a deposit is easily understood; the occurrence of whitlockite or martinite is much less easy to understand.

Pseudomorphs after brushite are known from the West Indian islands. Ornithite, described by Julien (1867) as forming small crystals in cavities in coral limestone and phosphate rock on Sombrero, was found by Frondel to be an apatite. Similar pseudomorphs of hydroxylapatite after brushite have been made artificially and are easily understood in the light of the incongruent solubility of brushite. The production of pseudomorphs of martinite after brushite, which

also occurred at Sombrero, is a more obscure process.

WHITLOCKITE AND MARTINITE

Whitlockite, corresponding to synthetic β - $\text{Ca}_3\text{P}_2\text{O}_8$, was described by Frondel (1941) as a late hydrothermal mineral in a granite pegmatite. It has subsequently been recognized from four insular localities in the West Indies, and from Oran (Bannister and Bennett, 1947). In three of the West Indian oc-

of monetite. No analysis is available, but CO_2 was present. Index of refraction 1.600.

SOMBRERO: Described as zeugite by Julien, and occurring as pseudomorphs after brushite. Two analyses are available (III, IV). Indices of refraction ω 1.608, ϵ 1.605.

UNSPECIFIED WEST INDIAN LOCALITY: Described as pyrophosphorite by Shepard, (1878) from a locality which was kept secret for commercial reasons. The material was reexamined by Frondel (1943) and found to

TABLE 53

	I	II	III	IV	V	VI
H_2O	4.52%	5.43%	3.07%	2.97%	0.39%	$\text{H}_2\text{O} - 0.21\%$
Org.	0.75					$\text{H}_2\text{O} + 1.79$
CaO	46.78	44.58	44.18	44.24	44.46	48.15
MgO	—	3.28	3.25	3.92	3.09	3.53
Na_2O	—	1.86	—	(NaCl 1.08)	—	0.0
K_2O	—	0.62	—	—	—	0.0
Al_2O_3	—	—	0.54	0.78	0.44	0.06
Fe_2O_3	—	0.27				0.05
MnO	—	—	—	—	—	0.01
P_2O_5	47.67	38.42	44.18	44.24	50.71	45.87
CO_2	—	1.54	tr.	0.48	—	0.0
SO_3	—	0.98	0.39	tr.	0.63	—
F	—	—	tr.	tr.	—	0.0
SiO_2 , insol.	0.20	0.47	—	—	0.37	0.04

I. Curaçao, martinite (Kloos, 1888).

II. Curaçao (Hendricks, Hill, Jacob, and Jefferson, 1931).

III, IV. Sombrero (Julien, 1867).

V. Unknown West Indian locality, pyrophosphorite (Shepard, 1878).

VI. Sebdo, Oran, Algeria (Bannister and Bennett, 1947), contains trace Cl and NH_4 .

currences there appears to be appreciable CO_2 and possibly essential water present, though such specimens are not distinguishable by X-ray powder pattern from the β - $\text{Ca}_3\text{P}_2\text{O}_8$. The material containing CO_2 had previously been described from Curaçao as martinite by Kloos (1888), and Fleischer (1944) suggests that the name martinite be retained for what otherwise might be termed carbonate-whitlockite. The nature of the occurrence is as follows:

CURAÇAO: Described originally as martinite, occurring at least in part as pseudomorphs after gypsum. Two rather discordant analyses (I, II) exist. Indices of refraction ω (Na) 1.607, ϵ 1.604.

LOS MONGES: Found by Frondel to form soft earthy masses under a botryoidal crust

be whitlockite. CO_2 is absent except from accidental inclusions of carbonate. Index of refraction 1.625.

It is evident that two somewhat different substances are involved. The Curaçao, Sombrero, and presumably the Los Monges minerals with about 3% to 5% water, partly no doubt non-essential, and some CO_2 have a low refractive index (1.60–1.61) and in the cases of the first two localities a low specific gravity (2.896 and 2.971, respectively). The material from the unspecified West Indian locality lacks CO_2 and any significant water and has a refractive index comparable to that of igneous whitlockite (1.628). The specific gravity of the latter (3.12) is near that calculated (3.19) for β - $\text{Ca}_3\text{P}_2\text{O}_8$. Apart from the information that on Curaçao the mineral

found is a pseudomorph after gypsum, and on Sombrero after brushite, nothing can be learned of the genesis of martinite, and the meaning of its occurrence remains problematic. The specimen from Sebdou, Oran, Algeria, studied by Bannister and Bennett, is to be regarded as whitlockite rather than martinite, since CO_2 is definitely absent. There seems, however, to be a small amount of water involved in the composition of the

THE APATITES

By far the most important of the calcium phosphates found in nature are the apatites. The best-known phosphate in igneous rock is fluorapatite, having a composition $\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$. This substance may be regarded as the source of most of the phosphate now circulating in the biosphere, and since it appears to be the only stable calcium phosphate in the presence of water and even

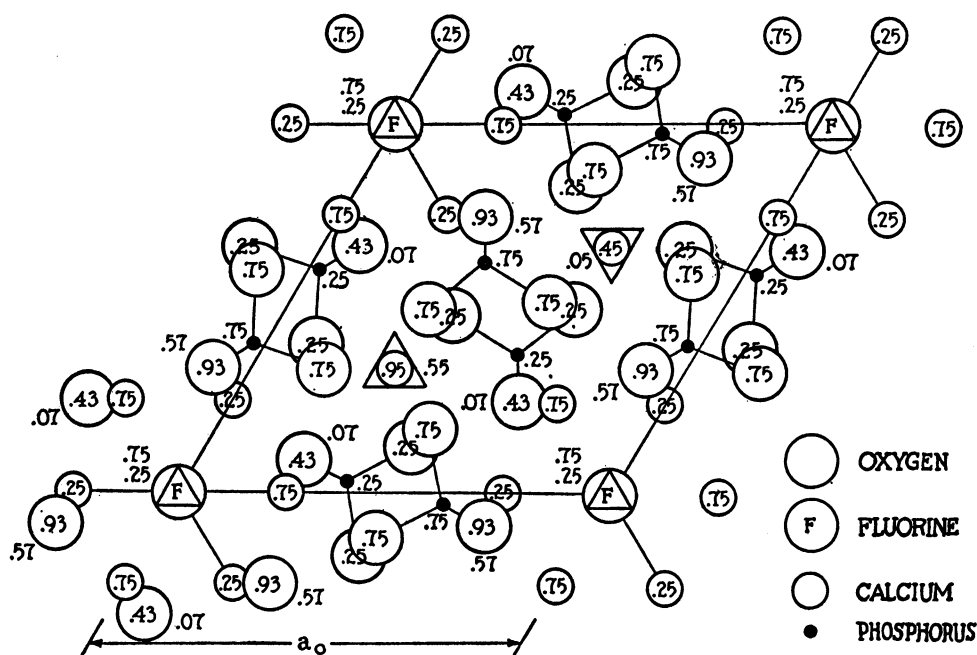


FIG. 103. The structure of fluorapatite. After McConnell.

mineral; the specific gravity is 2.96 as in martinite and the refractive index 1.616, nearer martinite than igneous whitlockite. The material was collected by Pallary, who discovered the taranakite at Tour Combes, and who labeled the whitlockite specimen minervite. It is therefore not at all improbable that the whitlockite of Sebdou occurred in a similar way to the taranakite at Tour Combes, and was discovered in a cave where it had formed from the phosphate of bat guano.

It is just possible that Malaguti's (1861) phosphatic pseudomorphs after gypsum from Patagonian guano might throw light on the problem of whitlockite, if any material still exists.

minute traces of fluoride, most of this circulating phosphate is fated to return to the lithosphere as the same mineral. Its structure has been elucidated by Náray-Szabó (1930), Mehmél (1930), Hendricks, Jefferson, and Mosley (1932), and McConnell (1938). McConnell's figure, after Mehmél, is reproduced here as figure 103. There has been some discussion of the position of the fluorine atoms, but the matter of debate concerns primarily their position on the c -axis perpendicular to the plane of the paper. While it appears that in chlorapatite the chlorine atoms do not occupy the same positions as the fluorine atoms of fluorapatite, solid solutions are common, and from the standpoint of the present contribution the matter

need not be further pursued. All that is needed at the present time is a knowledge of the general structure and of possible substitutions that can occur.

SUBSTITUTIONS INVOLVING THE HALOGENS

Chlorapatite, in which most of the fluorine is replaced by chlorine, giving $\text{Ca}_{10}(\text{PO}_4)_6\text{Cl}_2$, is known from igneous rocks. The sedimentary and biological apatites, though formed in aqueous solutions often extremely rich in chloride and always very poor in fluoride, practically never contain more than minute amounts of chlorine. In general the quantity present in phosphate rocks is less than 0.02% Cl and so no more than is found in the primary lithosphere (Jacob, Hill, Marshall, and Reynolds, 1933). One possibly significant exception to this generalization is discussed below.

Synthetic apatites of composition $\text{Ca}_{10}(\text{PO}_4)_6\text{Br}_2$ and $\text{Ca}_{10}(\text{VO}_4)_6\text{I}_2$ have been prepared. Nothing is known of the possibility of bromine substitution in natural apatites. The iodine compound $\text{Ca}_{10}(\text{PO}_4)_6\text{I}_2$ probably cannot be prepared in pure form, but it is likely that a very limited amount of iodine can be accommodated in the lattice of synthetic apatites containing phosphorus rather than vanadium (Wilke-Dörfust, Beck, and Plepp, 1928).

Treatment of fluorapatite with superheated steam causes a replacement of fluorine by hydroxyl groups. Very rarely the process has occurred in nature, producing relatively pure hydroxylapatite, $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$, in igneous rocks. The known cases are discussed by Mitchell, Faust, Hendricks, and Reynolds (1943). The same material can be made, as has been indicated, by hydrolysis of any calcium phosphate preparation less basic than hydroxylapatite. The occurrence of pure hydroxylapatite in sediments and biological deposits is, however, very problematic and is indeed hardly to be expected, because small amounts of fluoride are always available in the biosphere and because, when CO_2 is present in the hydrolyzing solution, another substitution, to be discussed below, also occurs.

Hydroxylapatite, when finely divided and exposed to water containing very minute amounts of fluorine, removes the element

quantitatively, and this reaction is the basis of various methods for removal of fluoride from drinking water. The great enrichment of fluorine in fossil bones is an example of the same process. During the formation of sedimentary phosphates in the sea, there is moreover a very definite tendency for fluorine to accumulate in quantities in excess of those required to form fluorapatite. The theoretical ratio by weight $\text{F}:\text{P}_2\text{O}_5$ in fluorapatite is 0.0891. In virtually all continental phosphate deposits, this ratio is exceeded, and values of about 0.1 appear to be usual, implying about 10% more fluorine than is demanded by the theoretical formula (Jacob, Hill, Marshall, and Reynolds, 1933). A similar excess of fluorine is well known in phosphatic nodules now forming on the floor of the ocean, as, for instance, in those recently analyzed by Dietz, Emery, and Shepard (1942). It has been supposed by most recent investigators of the apatites that, where no CaF_2 can be shown to exist as an independent mineral, the excess fluorine atoms replace oxygen atoms, various other types of substitution being postulated to maintain the electrostatic balance. Some apatites are known in which O^{--} apparently replaces F^- , but such substances are not relevant to the present discussion.

SUBSTITUTIONS INVOLVING CALCIUM

Artificial hydroxylapatites can be prepared (Klement, 1936; Klement and Dihn, 1938; Klement and Zureda, 1940) from calcium (atomic radius $r = 1.06\text{\AA}$), strontium ($r = 1.32\text{\AA}$), lead ($r = 1.32\text{\AA}$), and barium ($r = 1.43\text{\AA}$). The preparation of the comparable cadmium ($r = 1.03\text{\AA}$) apatite proved difficult, and no pure manganese ($r = 0.91\text{\AA}$) compound is known. Naturally occurring manganapatite, is, however, not infrequently encountered and may contain up to 10% of the calcium replaced by manganese. Smaller divalent ions do not replace calcium significantly, though the insignificant quantities of magnesium ($r = 0.78\text{\AA}$) often encountered in analyses may in part represent very limited substitution. The various cases in which monovalent or trivalent ions replace calcium are not relevant to the present discussion.

SUBSTITUTIONS INVOLVING PHOSPHORUS

Arsenic and vanadium both occur as minerals having the apatite structure, and synthetic arsenate and vanadate apatites are well known. The replacement of phosphorus by silicon and by sulphur must be considered in the general mineralogy and geochemistry of the apatites, but has no bearing on the problem of insular phosphates.

THE PROBLEM OF THE CARBONATE APATITES

It has long been known that most of the phosphates that have been discussed in the present work contain small amounts of CO_2 . The earlier analyses collected together by Dana (1892) show the presence of CO_2 in the minerals termed by him staffelite, but more correctly named francolite. Most of the older workers, before the development of X-ray crystallography, considered that carbonate present in sedimentary apatites represented a theoretical end member $3\text{Ca}_3\text{P}_2\text{O}_8 \cdot \text{CaCO}_3$, isomorphous with fluorapatite, $3\text{Ca}_3\text{P}_2\text{O}_8 \cdot \text{CaF}_2$, hydroxylapatite, $3\text{Ca}_3\text{P}_2\text{O}_8 \cdot \text{Ca}(\text{OH})_2$, etc. Hendricks, Jefferson, and Mosley (1932) gave a structural scheme by which this concept of carbonate-apatite could be reconciled with X-ray data. The whole question of the existence and nature of carbonate apatites has been examined more recently by McConnell (1943; Gruner and McConnell, 1937; Sandell, Hey, and McConnell, 1939) and has given rise to some controversy which seems to have subsided without being settled. The main point at issue has been the position of the carbon in the lattice. Gruner and McConnell, examining good material from Staffel, concluded that the introduction of carbon causes a slight contraction of the unit cell and that the X-ray data and analysis can best be interpreted by assuming that about one in 10 phosphorus atoms is replaced by carbon, forming CO_4 tetrahedra, and that calcium atoms on the threefold axis can also be replaced by carbon. The latter substitution has been the major point of disagreement. Bornemann-Starynkenvitch (1940) regards the carbonate apatites as solid solutions of $\text{Ca}_{10}\text{P}_6\text{O}_{24}\text{F}_2$ and $\text{Ca}_{10}\text{P}_8\text{CO}_{23}\text{F}_3$. Hendricks and Hill (1942) accept the substitution of carbon for phosphorus, but believe the car-

bon to be coordinated as CO_3 , four of such groups substituting for 3PO_4 tetrahedra.

TRICALCIUM PHOSPHATE HYDRATE

It is finally necessary to point out that it is possible to prepare a hydrated or α -tricalcium phosphate, which has the formula $\text{Ca}_3(\text{PO}_4)_3 \cdot 2\text{H}_2\text{O}$. This material forms β - $\text{Ca}_3\text{P}_2\text{O}_8$ when heated to constant weight at 900°C . The hydrated tricalcium phosphate possesses the apatite structure and forms solid solutions with hydroxylapatite. Tricalcium phosphate hydrate is now frequently considered to be the most important constituent of vertebrate bone (cf. Brasseur, Dallemagne, and Melon, 1946). It was supposed by Hendricks, Hill, Jacob, and Jefferson (1931) to be the main constituent of Curaçao phosphate, but as Frondel (1943) points out, this conclusion is probably invalid. Kazakov (1937) has apparently prepared another hydrate, but its relationship with any naturally occurring mineral is very problematical.

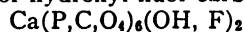
NOMENCLATURE

The most acceptable nomenclature appears to be:

dahllite for hydroxyl-carbonate apatite



francolite for hydroxyl-fluor-carbonate apatite



In both cases a limited substitution of O for $(\text{OH})_2$ or F_2 appears possible.

COLLOPHANE AND THE COLLOIDAL CALCIUM PHOSPHATES

The name collophane was introduced for the stratified, opal-like phosphate found on Sombbrero. Similar material from Nauru was termed nauruite by Elschner, and it evidently occurred at Ocean Island (translucent or subvitreous coherent phosphate of Owen), less abundantly at Makatea, at Ajawi, probably at Christmas Island, at Aldabra, and perhaps to a limited extent at Baker Island. It is described by Owen as containing casts of bubbles and evidently formed as a colloidal calcium phosphate that gelled and then crystallized.

Earlier workers did not associate the hard, dense apatite of igneous rocks with the sedi-

mentary calcium phosphates. Although Lasne (1890) indicated the probable identity of the two types of phosphate, the idea persisted that the sedimentary phosphates differed from apatite. It was often supposed, as Rogers (1922) strongly urged, that collophane represented an amorphous, and apatite a crystalline, form of the same substance. The investigation of phosphate rock by X-ray diffraction methods has, however, completely disposed of this idea. Even nauruite is evidently crystalline. It consists of a sub-microscopic aggregate of crystallites of apatite, this aggregate structure giving it an isotropic character. Its low specific gravity and refractive index are attributable to non-essential water held by capillarity or adsorbed (Fron del, 1943). No truly amorphous calcium phosphate has yet been found in nature, and the name collophane, if it is to be retained, should be applied as a varietal name for isotropic metacolloidal apatite.

The problem of the origin of collophane, as just defined, raises certain questions. It is apparently formed from highly supersaturated solutions. As far as the present writer is aware, solutions of the kind that might be expected to form collophane have not been observed in nature.

THE APATITES OF INSULAR PHOSPHATE DEPOSITS

Fron del states that he has examined powdery leached guano and found it to give an apatite X-ray diffraction pattern. It is probable that in most cases the less ancient material is to be referred to dahllite or hydroxyl-carbonate-apatite. It is, however, quite possible that small amounts of fluorine are more frequent in such material than the published analyses would suggest. If Sandberger's analysis of Sombrero collophane is correct and fluorine is not present in this substance in significant amounts, it must also be referred to dahllite. Hendricks, Hill, Jacob, and Jefferson considered that the Curaçao rock, which gave the β - $\text{Ca}_3\text{P}_2\text{O}_8$ pattern after being heated to constant weight at 900°C ., was best regarded as consisting of their hydrate apatite, or hydrated calcium triphosphate which has an apatite structure. As Fron del points out, hydroxylapatite behaves in the same way, and he regards the Curaçao rock

as dahllite. It is certainly not fluorine free, though poorer in the element than are the other old insular phosphates.

All the other material examined by X-ray methods is probably referable to francolite. This is specifically true of the Nauru phosphate examined both by Fron del and by Hendricks, Hill, Jacob, and Jefferson, and of the Ocean and Christmas Island samples studied by the latter authors.

In view of the fact that some of the substitutions discussed above are of some biogeochemical interest, the quantities of certain of the minor constituents of coprogenic phosphates may be profitably discussed.

FLUORINE IN INSULAR PHOSPHATES

Peruvian guano probably of contemporary origin contains, according to Jacob, Hill, Marshall, and Reynolds, 0.06% F, the F:P₂O₅ ratio being 0.0042. Braun's figures are slightly higher but probably less reliable. They are more likely to be too high than too low and probably indicate little enrichment of fluorine in the ancient Chilean deposit of Huanillos. It is evident that the fluorine of coprogenic phosphates is derived from some source outside the guano deposit.

For the post-Pleistocene phosphatic guanos of slightly elevated coral islands, there is a single determination by Jacob, Hill, Marshall, and Reynolds, from Juan de Nova, for which locality Lacroix states fluorine to be absent from the phosphate below the guano, and several old analyses by Gilbert. Since Gilbert's analyses for the fluorine of Curaçao phosphate are low, one in fact lower than the more recent analyses of Jacob, Hill, Marshall, and Reynolds, they are probably not excessive and may be accepted tentatively:

	F	F:P ₂ O ₅
Sydney	0.40%	0.0116
Fanning	1.01	0.0296
Browse	0.34	0.0108
Lacépède	0.77	0.0229
Houtman's Abrolhos	1.25	0.0371
Juan de Nova	1.68	0.0520

It has already been indicated that the Fanning Island deposit and probably that of Juan de Nova were not due to a contemporary bird colony, while the Sydney Island and probably the Lacépède Island deposits are

due to recent populations. No detailed conclusions can be drawn from these determinations, but taken as a whole they provide a not unreasonable series of intermediates between nitrogenous guano and Pleistocene rock phosphate.

The phosphatic rock of the elevated islands has been analyzed a number of times. The determinations of Jacob, Hill, Marshall, and Reynolds alone are certainly reliable; those for Curaçao by Gussefeld and Gilbert may be. Those by other authors for other islands are most problematic. The individual analyses summarized below all are from Jacob, Hill, Marshall, and Reynolds; the ranges given in parentheses are from the works of other investigators cited in the main body of the text.

	F	F:P ₂ O ₅
Ocean Island	2.97%	0.0737
	2.97	0.0736
	3.29	0.0805
	(1.3-2.3)	0.0364-0.0525)
Nauru	2.62	0.0673
	2.48	0.0635
	2.10	0.0536
	(1.88, 2.12)	0.0486, 0.0540)
Makatea	3.42	0.0901
	3.25	0.0850
	(tr., 1.30 tr.,	0.0339)
Angaur	2.96	0.0740
	(0-1.35	0.0209)
Christmas Island, Indian Ocean	1.32	0.0335
	1.05	0.0262
	(0.54	0.0137)
Curaçao	0.91	0.0240
	0.71	0.0181
	0.75	0.0194
	0.38	0.0093
	(0.18-0.48	0.0044-0.0120)

In addition to these determinations for insular phosphates, the nodular phosphate from Langebaan Road, in South Africa, is probably a Pleistocene deposit of avian origin. Here most of the nodules consist largely of a material giving a F:P₂O₅ ratio of 0.09 and evidently fluorapatite, though one nodule of a less resinous luster gave a ratio of 0.07 and presumably contained francolite.

Apart from this occurrence, almost all the phosphate rock of avian origin has a F:P₂O₅ ratio below that of fluorapatite, and so contrasts strikingly with the vast majority of continental sedimentary phosphates and with phosphatic nodules now forming on the ocean floor where the ratio is in excess of that of fluorapatite. There can be little doubt that the major deposits differ characteristically from one another, though the amount of variation to be expected within a deposit is hard to assess. If the analyses of Jacob, Hill, Marshall, and Reynolds alone are reliable, Makatea phosphate is clearly richer in fluorine than the others, approaching fluorapatite in its composition. The statements of other authors that Makatea phosphate is low in fluorine may simply be wrong, or the deposit may vary greatly.

The difference between Ocean Island and Nauru phosphate apparent in the analyses of Jacob, Hill, Marshall, and Reynolds is borne out by other statements that Ocean Island phosphate contains more fluorine than that of Nauru, statements which may indicate significant relative differences between analyses that are not reliable on an absolute basis. There can be no doubt whatever that these Pacific phosphates are far richer in fluorine than the Curaçao phosphate. The Christmas Island deposit probably occupies an intermediate position.

On an oceanic island composed of coral rock, there can be only two sources of fluorine, namely, from sea water distributed as spray and from the atmosphere. The continental phosphates, including perhaps the Langebaan Road deposit, may receive fluorine from circulating ground water, though most of the marine phosphorites were probably fully supplied with the element before uplift.

From the mean mass of phosphate rock per unit area, namely, 486 grams per cm², and the mean fluorine content of 3.08%, it is easy to calculate that Nauru must have received about 15 grams of fluorine per cm² to account for the whole of the element found in the phosphate. The fluorine content of sea water is about 1.4 milligrams per liter, so that to supply the island would be equivalent to the removal of all the fluorine from 10,700 liters of water per cm² of island surface. If it is

assumed, as a limiting and most improbable case, that 10% of the rainfall observed at Nauru is actually sea spray, which is certainly excessive in view of the vegetation of the island, the delivery of the fluorine would require just over half a million years. If a marine transgression had occurred after phosphatization of the island, there would be no difficulty in deriving the fluorine from the sea, but there is no evidence of such a transgression.

No data appear to be available as to the fluorine content of uncontaminated rain. The observations of Zies (1929) indicate that the fumaroles of Katmai produce annually 180,000 tons of fluorine. This corresponds to 3.6×10^{-8} grams per cm^2 of the earth's surface. Little information is available about other volcanoes, but it is probably not unreasonable to set an upper limit between 10^{-8} and 10^{-5} grams per cm^2 per year for fluorine from this source. The supply of 15 grams per cm^2 at this rate would therefore take from 1,500,000 to 15,000,000 years.

The estimates given above indicate that neither marine spray nor atmospheric fluorine is likely to have produced the observed conditions on Nauru, unless it can be assumed that they have acted for periods of the order of a million years. This is just possible if the fluorine has been added quite continuously from both sources, assuming that the deposit was formed during one of the early interglacials. If, however, Jacob, Hill, Marshall, and Reynolds are correct in their belief that the Nauru phosphate has a relatively uniform fluorine content, it is very difficult to see how this condition would have been achieved by gradual delivery of fluorine at the surface. Since none of the rock is fully saturated, one would expect a gradient in fluorine from the superficial to the deep parts of the deposit. It is moreover not clear how the subvitreous variety of Nauru phosphate termed nauruite by Elschner, which must be relatively impermeable, could have contained fluorine, except perhaps in very small amounts at the surface, unless the element was incorporated at the time the mineral formed.

The Curaçao phosphate is also of interest in relation to the problem of fluorine. All determinations are very low, and there can

be no doubt that the material contains much less fluorine than the other insular phosphates. It also appears to contain more chlorine, so that in the sample analyzed by Jacob, Hill, Marshall, and Reynolds, lowest in fluorine, the atomic ratio F:Cl is approximately 5:1. Moreover the magnesium and sodium contents are higher than those of Ocean or Nauru phosphate. The Curaçao rock indeed shows more evidence of contact with sea water than do the other specimens, in spite of its low fluorine content.

It is evident that the problem of the origin of the fluorine in the deposits of the elevated phosphatic islands is far from solved. It is obviously a matter of the greatest geochemical interest to have a long series of good determinations of fluorine throughout well-described profiles in several parts of Ocean Island, Nauru,¹ Makatea, and Curaçao. The past exploitation of guano and phosphate deposits has destroyed so much invaluable paleoclimatological and geochemical data that it is encouraging to find a case where there is still time to assemble the information. If Jacob, Hill, Marshall, and Reynolds are correct in their postulate that each island has a relatively constant and characteristic fluorine content, the most reasonable explanation would be that at the times when each deposit formed, large and characteristic quantities of atmospheric fluorine were available. This hypothesis may prove quite unnecessary; the mere fact that it can be proposed without doing violence to the few known facts indicates how much work is needed on the problem. If such a hypothesis survives further tests, it is obviously likely to develop in a most interesting way. Whatever views on the source of the fluorine may finally be acceptable, solution of the problem is certain to contribute to a far greater field than that of the geochemistry of insular phosphate deposits.

Apart from the alleged lack of fluorine in the chiropterite of the Drachenhöhle, Mixnitz, the only data on the phosphatic deposits of caves appear to be from the Grotte de la Coquille, in the calcareous deposits of which

¹ The Imperial Phosphate Commission kindly informed me that no information of this sort exists for Ocean Island or Nauru.

cave (analyses I, III, IV, and V, of table 50) the fluorine content varied from 0.90% to 2.10% and the ratio $F:P_2O_5$ from 0.0512 to 0.0762. In sample VI, which contains much aluminum phosphate, the fluorine content was 0.44% and the ratio 0.0155. These figures strongly suggest that the main calcium phosphate in the chiropterite of this locality was also francolite.

OTHER HALOGENS IN INSULAR PHOSPHATES

Chloride has often been recorded in the analyses of phosphatic guano, often as NaCl. In such cases the presence of sea salt may reasonably be suspected. The few determinations made for the phosphate rock of elevated islands by Jacob, Hill, Marshall, and Reynolds, are as follows:

Ocean Island	0.01%
Nauru	0.01
Christmas Island, Indian Ocean	0.02
Curaçao	0.14, 0.16
Connétable (barrandite)	tr.

The Curaçao figures have already been discussed. It is unfortunate that there is no indication whether or not this chloride was water soluble; if not, it would probably indicate that the chloride was present in the apatite lattice. Nothing is known of the bromine content of insular phosphates.

Iodine is probably concentrated to a limited extent in the insular apatites. The following determinations from Wilke-Dörfurt, Beck, and Plepp (1928) and from Jacob, Hill, Marshall, and Reynolds (1933) are available:

	MILLIGRAMS PER KILO
Ocean Island	18.3
Nauru	16.7, 19.1, 16.5
Christmas Island, Indian Ocean	75.4
Curaçao	37.0, 122
Walpole Island	25.2

These contrast very markedly with the virtual absence of iodine in the barrandite of Connétable. If the iodine were an accidental inclusion derived from sea spray, there is no reason why the Connétable phosphate should contain so much less than the others. It is reasonable to suppose that the iodine is pres-

ent in the calcium phosphates because it can form an integral part of one of their components. Considering a long series of sedimentary continental phosphates, Jacob, Hill, Marshall, and Reynolds usually found an enrichment comparable to that in insular phosphates. The quantity present showed no correlation with the quantity of organic matter. It seems quite probable that, although the existence of $Ca_{10}(PO_4)_6I_2$ even as an artificial compound is improbable, very limited substitution of I for F is possible in the apatite lattice (Wilke-Dörfurt, Beck, and Plepp, 1928) and that this accounts for the slight enrichment of iodine of marine origin in insular and other sedimentary calcium phosphates.

SUBSTITUTIONS FOR CALCIUM AND PHOSPHORUS

The only determination of strontium is that of Lacroix on the phosphate that lay below the guano at Juan de Nova. This material contained 0.17% SrO, corresponding to a Ca:Sr ratio of about 100:0.4. Such a ratio indicates strong exclusion of strontium relative to sea water and possibly a slight enrichment relative to coral limestone. The analysis is unlikely to be very accurate, and further investigation is desirable.

No clear evidence relative to the possible substitution of calcium by alkalis or other alkaline earths is available. Where sodium and magnesium are reported in analyses, it is never certain that they do not represent mechanical admixture of sea salt or dolomite.

It is unfortunate that so little information exists relating to the manganese content of insular phosphates. The Curaçao deposit contained less than 0.003% MnO, which is low for any ordinary rock. There is evidence that black manganese oxide was formed in association with calcium phosphate deposition at Christmas Island and in the Drachenhöhle at Mixnitz. The very low manganese content both of the Curaçao material and most continental phosphatic sediments probably indicates that, in the normal circumstances of deposition of such phosphates, the redox potential is never low enough to permit the existence of significant quantities of manganous ions in solution. As has been pre-

viously indicated, in the formation of igneous apatites limited substitution of calcium by manganese is common. As is indicated below, manganese is apparently enriched in some magnesium minerals in bat caves.

The only other information on minor constituents relates to four elements determined in the Curaçao material, namely, vanadium, arsenic, copper, and zinc. The contents were as follows:

V_2O_5	0.01%
As_2O_5	0.00076–0.0012
CuO	0.005
ZnO	0.045

The vanadium content may represent slight

enrichment in view of the poorness of sea water and limestone in the element. The most interesting of the four determinations is that for zinc, which is higher than the values obtained for 22 continental phosphates by Jacob, Hill, Marshall, and Reynolds, who found not more than 0.025% in the entire series and not more than 0.001% in 20 of their samples. The meaning of this enrichment in zinc is obscure, but the occurrence suggests that further studies of the element should be made.¹ The occurrence of zinc in the fossilized bone of *Ursus spelaeus* from the Grotte de la Coquille (Gautier, 1894) may perhaps be recalled in relation to this occurrence.²

MAGNESIUM PHOSPHATE MINERALS

The magnesium and magnesium ammonium phosphate minerals that have been recorded are of considerable interest. The well-established species appear to be:

Bobierite, $Mg_3P_2O_8 \cdot 8H_2O$, occurring at Mejillones, and probably in Skipton Cave, as well as in localities not associated with guano.

Newberyite, $MgHPO_4 \cdot 3H_2O$, occurring at Mejillones, Skipton Cave, Ascension, and the Tunnel du Cormoran in Réunion.

Struvite, $(NH_4)MgPO_4 \cdot 6H_2O$, occurring at Saldanha Bay, in Patagonian guano, probably at Baker Island, perhaps in some Peruvian guano ("concrete guano") and in the Skipton Cave, as well as in other places where decomposing organic matter is leached by magnesium-rich solutions.

Hannayite, $Mg_2H_2(PO_4)_2 \cdot MgH_2(NH_4)_2(PO_4)_2 \cdot 8H_2O$, known only from the Skipton Cave.

Schertalite, $Mg(NH_4)_2H_2(PO_4)_2 \cdot 4H_2O$, known only from the Skipton Cave.

Dittmarite, $Mg(NH_4)PO_4 \cdot 2Mg_2H_2(PO_4)_2 \cdot 8H_2O$, known only from the Skipton Cave.

It is probable that in every case an extraneous source of magnesium is required to form these minerals. At Mejillones this was evidently provided by sea spray, and the same is probably true at Saldanha Bay, Baker Island, and in Patagonia. In the Tunnel du Cormoran, Réunion, the decomposition of basalt apparently provided the magnesium, and this is probably true also at the Skipton Cave and at Ascension.

Though artificial struvite appears stable at

room temperatures in ordinary laboratory air over periods of time of ordinary observation, it would seem from MacIvor's account of the Skipton Cave that over long periods in dry guano only newberyite and perhaps bobierite are stable. It is reasonably certain that the three minerals confined to this locality represent the results of a very special set of

¹ Goldschmidt (1938) indicates that Brundin observed up to 0.1% Zn in sedimentary phosphates such as those from the South Sea Islands and that such phosphorite could contain up to 0.01% cadmium also. It is most unfortunate that these results seem never to have been published in detail.

² Tremearne and Jacob (1941), in tables unfortunately overlooked in the preparation of the present work, indicate 24.9 p.p.m. As in Peruvian guano containing 14.4% P_2O_5 and from 5.1 p.p.m. in Nauru to 76.2 p.p.m. in Kita Daito phosphate. A number of phosphatic guanos from the Seychelles and all the important insular phosphates were studied. It is evident that limited substitution of As for P is usual. After the present contribution had gone to press, two papers on the minor constituents of rock phosphate, by Jolibois and Hébert (1946) and by Robinson (1948) have become available. The first-named authors note qualitative spectrographic traces of tin, antimony, zirconium, beryllium, and lithium, as well as most of the elements recorded by previous authors, in the majority of the rock phosphates that they examined, including one from Oceania (? Makatea). Robinson records, from Nauru phosphate, 2 p.p.m. molybdenum and 110 p.p.m. rare earth oxides, and from Curaçao phosphate, 1 p.p.m. molybdenum and 50 p.p.m. rare earth oxides. The figures for rare earth oxides are lower than any given by nine continental rock phosphates (140–1550 p.p.m.); the figures for molybdenum are also very low but can be paralleled by continental specimens from Tennessee (1–2 p.p.m.), though not from other North American (5–208 p.p.m.) or Old World (9–62 p.p.m.) localities.

conditions intermediate between those in which struvite is formed and those in which the magnesium phosphates without ammonia alone are really stable. Though a number of other magnesium phosphates are known in the laboratory, they do not seem to throw light on this remarkable occurrence.

It is of interest that at least the magnesium phosphate minerals from Skipton Cave exhibit very definitely the expected slight replacement of Mg ($r=0.78\text{\AA}$) by Mn ($r=0.91$

$\text{\AA}$) as can be seen from MacIvor's analyses. No other guano minerals appear to be enriched in manganese.

Finally, it is desirable again to emphasize the importance of investigating anew the supposed magnesium borophosphate described by Domeyko (1878, 1880) and Krull (1892) from Mejillones, which, if it is a valid mineral species, presumably represents another product of the effect of sea spray on partially leached guano.

ALUMINUM AND FERRIC PHOSPHATE MINERALS

The action of phosphatic solutions on igneous rocks or on their decomposition products frequently produces aluminum and ferric phosphates of considerable mineralogical, geochemical, and climatological interest. Before the well-established cases are discussed it is necessary to point out that in a good many analyses of phosphatic guanos, from all parts of the world except the coral atolls of the open oceans, Al_2O_3 and Fe_2O_3 often appear as important minor constituents. This is true of some Mejillones analyses, several analyses of old deposits on the islands of Lower California, in most of the analyses of phosphatic deposits from the Palau and Mariana groups, and in many of those from the Riu Kiu Islands, in those of the insular deposits of Saldanha Bay, the Kuria Muria Islands, and possibly Farquhar Atoll, and in a number of West Indian analyses. In many of these cases there is obviously residual material mixed with calcium phosphate, but without any evidence that it has been phosphatized. The analytical evidence suggests, however, that in some samples from Mejillones, Elide Island, the Kuria Muria Islands and Navassa some $(\text{Al,Fe})\text{PO}_4$ was actually present.

MINERALS OF COMPOSITION $(\text{Al,Fe})\text{PO}_4 \cdot 2\text{H}_2\text{O}$ ASSOCIATED WITH INSULAR PHOSPHATIZATION

Two isodimorphous series are known:

	ORTHO-RHOMBIC	MONO-CLINIC
$\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$	Variscite	Metavariscite
$(\text{Al,Fe})\text{PO}_4 \cdot 2\text{H}_2\text{O}$	Barrandite	Clinobarrandite
$\text{FePO}_4 \cdot 2\text{H}_2\text{O}$	Strengite	Phosphosiderite

There can be little doubt that these min-

erals represent the normal products of phosphatization of igneous and other aluminosilicate rocks in tropical and subtropical regions of markedly seasonal rainfall. Lacroix (1906) compares the formation of these ferric and aluminum phosphates in the presence of phosphatizing solutions to laterization, "*cette autre maladie tropicale des roches silicatées*," in the absence of phosphate. In both processes silica and the more soluble bases are lost.

Mineralogical determinations of the products of this phosphatization have been made most completely by McConnell for Gran Roque, where barrandite was identified, and for Malpelo Island, where variscite and metavariscite occurred in one sample, strengite and phosphosiderite in another. Lacroix identified the phosphate of Ihleu das Cabras and Grand Connétable as barrandite, and Du Toit concluded that the material from Constable Hill, Saldanha Bay, was the same mineral mixed with siliceous matter. Most or all of the phosphates described as redondite are no doubt barrandite; McConnell (1950) finds both barrandite and clinobarrandite in Redonda material.

All the relevant chemical data are set out in table 54. It will be seen that with the exception of the specimens from Alta Vela, in every case there is a fair approximation to a ratio $(\text{Al,Fe})_2\text{O}_3:\text{P}_2\text{O}_5$ as 1:1. The water contents are very variable, but are usually in excess of $\text{H}_2\text{O}:\text{P}_2\text{O}_5$ as 4:1. This may be owing to inclusion of some non-essential water in computation, but it seems reasonably certain that not all the water given off below 110°C . must be disregarded. The lowest water content is given by the Gran Roque specimen known on optical and X-ray diffraction data to be barrandite. There may well be

analytical reasons for low water contents, which do not appear in the reports of the analyses. The procedure used in the analyses of the Saldanha Bay specimens is not clear. No very great weight therefore should be attached to the variations in the ratio $\text{H}_2\text{O}:\text{P}_2\text{O}_5$. Even greater departures from the ratio of 4:1 would have been apparent if more of the Kita Daito Jima samples had been included (cf. III, table 54). It is, however, certain that the mode of formation of the deposit on this island is so unlike that of the other localities that no great similarity in the product of phosphatization would be expected. The analyses presented were selected to show that even here a material chemically like that found at the other localities can be formed.

The high water content of the so-called myersite of Necker Island can be paralleled by variscite-like minerals formed under other conditions and apparently containing more water than typical variscite, but until more is known of the structure of these phosphates no interpretation of the occurrence is possible.

The Alta Vela phosphate is the least well known. The analyses seem to indicate something very different from the minerals found on the other West Indian islands. It is, however, by no means certain that the phosphate does not represent partial phosphatization of a partially decomposed rock, and so may consist of $(\text{Al},\text{Fe})\text{PO}_4 \cdot 2\text{H}_2\text{O}$, hydrated oxides, and siliceous material. Nothing further can be said without a reëxamination.

The analyses collected together in table 54 together with certain others from Redonda given in the text exhibit a series of minerals ranging from practically pure aluminum phosphate, as in the case of Îlot de la Perle, Necker Island, or one of the Kita Daito Jima samples, to the relatively pure ferric phosphate of Malpelo Island. The ratio of the mean contents $\text{Al}_2\text{O}_3:\text{Fe}_2\text{O}_3$ is, for the entire series,¹ 100:52.6 by weight, or 100:32.9 by molecular proportion. Since the atomic ratio $\text{Al}:\text{Fe}$ in the accessible lithosphere is 100:29.7 (Goldschmidt, 1938), there does not seem to be any significant average enrichment in either element.

¹ Excluding XXV, Île de Corail, where the high FeO content introduces an uncertainty as to whether some unaltered iron-containing mineral may not be present.

Where titanium is recorded, it is probably present as titaniferous minerals included in the analyzed specimen and is of no particular geochemical interest, except as a standard of reference.

Manganese is practically absent from the Connétable barrandite, and relative to titanium much impoverished in the Malpelo sample ($\text{TiO}_2:\text{MnO}=100:1.5$) when comparison is made with the original augite-andesite ($\text{TiO}_2:\text{MnO}=100:5.8$).

Several minor constituents of the barrandite of Grand Connétable have been determined by Jacob, Hill, Marshall, and Reynolds. The low halogen content of the barrandite is to be expected and has already been noted.

Connétable barrandite contains more zinc than any continental calcium phosphate analyzed but is exceeded by Curaçao phosphate in zinc content. It contains rather more copper than the Curaçao phosphate and much more than most, but not all, continental phosphates. It contains more arsenic than Curaçao phosphate, but not more than some continental calcium phosphates.

Where detailed chemical studies have been made, the most interesting finding is the presence of more than minute traces of chromium, at both Gran Roque and Grand Connétable, but not at Malpelo. Curaçao phosphate, the only insular calcium phosphate hitherto analyzed for chromium, contains no detectable amount; continental calcium phosphates frequently contain the element. It is evident that no interpretation of the minor metallic constituents in terms of atomic substitutions is at present possible.

There appears to be considerable variation in the details of the mode of origin of these minerals. On Malpelo Island, the Ihleu das Cabras, Perle, and Clipperton Island, the phosphatization represents a direct surface alteration. The silica of the altered rock appears as blebs of quartz or as chalcedony, but it is evident from analysis that much silica is lost. Quartz in the original rock is apparently left unattacked. At Saldanha Bay the main process appears to have been the phosphatization of fragments of granite or porphyry that fell into the guano deposit. The larger fragments still remain embedded in the phosphate and are relatively unphosphatized

TABLE 54

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII	XIX	XX	XXI	XXII	XXIII	XXIV	XXV
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
H ₂ O –	3.80	23.0	26.1	25.14	21.88	18.51	19.33	4.19	24.00	24.30	24.20	22.06	17.99	22.56	24.5	12.17	22.87	21.38	5.89	21.24	22.58	(7.41)	(10.28)	(13.17)	23.60
H ₂ O +	14.90								12.99					2.27	0.78					3.14	2.50				
Al ₂ O ₃	4.11	25.9	28.55	31.60	13.16	21.20	20.22	21.98	16.60	13.40	24.80	24.75	15.16	22.12	34.20	13.03	16.24	12.33	21.40	25.59	30.14	16.11	14.48	17.29	25.39
Fe ₂ O ₃	33.40	7.4	1.01	1.20	26.33	7.38	7.23	2.79	14.40	16.60	5.20	8.25	18.94	9.83	—	1.91	12.41	23.89	13.65	8.03	3.52	9.21	8.71	8.73	6.51
FeO	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.20
Cr ₂ O ₃	0.00	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.75	0.75	—	0.014	—	—	—	—
MnO	0.08	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.003	—	—	—	—
TiO ₂	5.42	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.23	—	0.13	—	—	—	1.10
CaO	0.00	—	0.60	—	—	—	—	—	0.57	—	—	—	0.08	0.15	tr.	0.37	2.66	—	0.40	1.40	0.00	1.09	1.71	3.06	2.12
MgO	0.00	—	0.23	5.07	—	—	—	—	—	—	—	—	0.12	0.06	tr.	0.57	—	—	—	tr.	0.25	—	—	—	0.24
Na ₂ O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.07	—	—	—	1.06
K ₂ O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.06	—	—	—	tr.
P ₂ O ₅	33.74	38.5	41.29	44.40	39.38	20.07	26.23	10.86	43.20	38.20	40.20	42.90	38.02	40.05	41.20	19.11	31.60	38.55	44.30	39.16	44.50	27.24	28.11	32.63	33.54
SiO ₂ insol. etc.	4.31	5.0	3.05	1.43	2.26	32.84	26.99	27.19	1.60	—	—	—	5.96	2.65	—	52.07	13.18	2.07	6.66	1.70	1.49	38.94	36.71	25.12	5.25
Molecular ratios																									
H ₂ O	4.37	4.71	5.00	4.46	4.39	7.27	5.82	12.59	4.37	5.02	4.75	4.14	4.57	4.77	4.70	5.03	5.61	4.38	1.61	4.80	4.30	(2.15)	(2.88)	(3.18)	5.54
(Al, Fe) ₂ O ₃	1.05	1.11	0.97	1.01	1.06	1.86	1.33	3.09	0.83	0.88	0.97	0.98	1.00	1.02	1.16	0.97	1.05	0.99	0.95	1.09	1.02	1.09	0.99	0.97	1.22
P ₂ O ₅	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

I. Malpelo Island, phosphatized augite-andesite.
II. Clipperton Island, fully phosphatized trachyte.
III. Necker Island, so-called myersite, phosphatized basalt.
IV. Kita Daito Jima, most phosphatic sample, compact, pale green, phosphatized pumiceous clay (from hypersthene-andesite pumice).

V. The same, pale green, compact.
VI-VIII. Alta Vela.
IX. Redonda, so-called redondite, original-analysis, phosphatized basaltic lava.
X-XIV. The same.
XV. flot de la Perle, Martinique, phosphatized trachyte.
XVI. Testigos Island.
XVII. Centinella.

XVIII-XIX. Gran Roque, phosphatized diabase (mainly gangue material of faults).
XX-XXI. Grand Connétable, phosphatized gneiss and diabase.
XXII-XXIV. Constable Hill, Saldanha Bay, phosphatized granite porphyry (water content assumed from undetermined material of analysis).
XXV. Île de Corail, Los Archipelago.

internally. It is interesting to note that in the Chilean deposits in conditions of extreme aridity, as at Pabellón de Pica or Mejillones, granite blocks embedded in guano have undergone only the slightest surface alteration.

Both Gautier (1894) and Leitmeier and Hellwig (1920) found that hot ammonium phosphate reacted with kaolin. The latter authors obtained 30% to 40% AlPO_4 by this method. Feldspar and undecomposed rock were not attacked. Initial alteration of the rock is therefore likely to facilitate phosphatization, though with the long periods of time available in nature, such preliminary decomposition is unnecessary. In natural phosphatization feldspars are attacked as at Saldanha Bay, though less easily than the glassy ground substance of the Constable Hill granite porphyry. Du Toit described a white material from part of the Saldanha Bay deposit that he believed to be phosphatized clay. Elschner maintained that at Necker Island decomposition of the basalt preceded phosphatization, and this decomposition he attributed to ammonium oxalate derived from guano. The evidence is quite inadequate.

At Gran Roque petrographic studies appear to indicate that dahllite was first formed, and that this calcium phosphate was later replaced by barrandite. No other evidence of the intermediate formation of an apatite has been described.

If Tempany's account of Redonda proves acceptable, the deposit was formed neither by the direct phosphatization of volcanic rock, nor by the phosphatization of alteration products, but by solution of guano in the volcanic magma. In spite of Tempany's arguments some degree of skepticism is probably justifiable.

MINERALS FORMED BY INLAND EPIGEAN PHOSPHATIZATION IN AUSTRALIA¹

The analyses in table 55 relate to the two rather curious cases of inland phosphatiza-

¹ Dolerite in sandstone has apparently been replaced by iron and aluminum phosphate on the farm Zoetendalesvley 889, Potgietersrust District, Transvaal, as the result of the action of phosphate solutions supposedly from the droppings of birds and mammals living in mountain cliffs above the locality. A similar material occurs at Kluitjiesfontein 369, Middelburg District (Union of South Africa, Geological Survey, *in litt.*).

TABLE 55

	I	II	III	IV	V
H ₂ O —	1.14%	1.97%	6.59%	16.94%	10.36%
H ₂ O +	19.82	20.98	12.28	2.65	1.74
Al ₂ O ₃	17.81	20.45	12.73	17.12	7.06
Fe ₂ O ₃	17.66	12.66	32.82	6.78	24.25
FeO	0.03	0.20	0.0	—	—
MnO	0.27	0.0	0.22	—	—
Cr ₂ O ₃	tr.	0.73	0.0	—	—
CaO	0.0	0.0	tr.	2.06	2.32
MgO	0.27	0.0	0.73	0.92	—
K ₂ O	0.29	0.96	7.88	—	—
Na ₂ O	0.19	tr.	0.13	—	—
P ₂ O ₅	40.23	42.19	26.69	35.22	17.37
SiO ₂	1.92	0.0	0.0	17.30	36.72
Molecular ratios					
H ₂ O	4.11	4.29	4.53	4.57	5.75
(Al,Fe) ₂ O ₃	1.01	0.94	1.76	0.88	1.90
P ₂ O ₅	1.00	1.00	1.00	1.00	1.00
K ₂ O	—	—	0.36	—	—

- I. Lake Weelhamby, brown "redondite" (TiO₂, 0.45%).
- II. Lake Weelhamby, green "redondite" (TiO₂, 0.21%).
- III. Lake Weelhamby, leucophosphorite (also NiO tr.), (NH₄)₂O, 0.09%.
- IV. Elder Rock, Paratoo Siding, isotropic mineral (molecular ratios computed assuming CaO as Ca₁₀(P₂O₅)₃·(OH)₂).
- V. Elder Rock, Paratoo Siding, anisotropic mineral (molecular ratios computed on same assumption).

tion by avian excreta, recorded from Australia. The main mineral at the Lake Weelhamby occurrence obviously has the composition $(\text{Al,Fe})\text{PO}_4 \cdot 2\text{H}_2\text{O}$. It was described as redondite, the name presumably being regarded as synonymous with barrandite. The mineral has been produced as the result of the direct phosphatic alteration of serpentine, and the subfibrous structure of the actinolite of the parent material can be made out in the alteration product. The excess silica is apparently at least in part represented by chalcedony. Of the minor constituents that are likely to be present in the original serpentine, it is interesting to find that an appreciable amount of chromium has been incorporated into the more aluminous specimen of barrandite, as is also the case at Gran Roque.

The potassium ferric aluminum phosphate, leucophosphorite, occurred in small quantities associated with the barrandite. It was compared to minervite by Simpson, but apart from not being crystalline, it differs greatly in chemical composition; it is a basic phosphate, while taranakite is acidic. The occurrence of potassium in leucophosphorite is, however, of some interest, particularly in view of the considerable enrichment over the content that might be expected in the serpentine.

Though the Weelhamby phosphate must have been formed at a time when the lake, now a dry salina, contained enough water to support food for a cormorant population, it is reasonably certain that the climate during such a pluvial period would be characterized by strongly seasonal rainfall. In general the deposit is in accord with Lacroix's hypothesis of the association of the $(\text{Al,Fe})\text{PO}_4 \cdot 2\text{H}_2\text{O}$ minerals with seasonal rainfall in warm regions. It is not improbable that the leucophosphorite derived its potassium from biological sources under some quite special conditions. The two minerals from Elder Rock, Paratoo Siding, are not well characterized. They are apparently formed by the phosphatization of sedimentary rocks, described as ferruginous quartzite and coarse breccia by birds, perhaps eagles, that occupied the top of the rock. The isotropic material probably belongs with the $(\text{Al,Fe})\text{PO}_4 \cdot 2\text{H}_2\text{O}$ series; part of the water lost below 120°C .

may be non-essential. It is at any rate certain that the mineral has nothing to do with evansite to which Mawson and Cooke compared it. The anisotropic mineral is a basic phosphate, approximating to $2(\text{Al,Fe})_2\text{O}_3 \cdot \text{P}_2\text{O}_5 \cdot 5\text{H}_2\text{O}$.

OTHER ALUMINUM AND FERRIC PHOSPHATES FORMED UNDER TROPICAL EPIGEAN CONDITIONS

The main exception to the generalization that under tropical or subtropical conditions the products of phosphatization of aluminum-containing and iron-containing materials are chemically $(\text{Al,Fe})\text{PO}_4 \cdot 2\text{H}_2\text{O}$ is provided by Trauhira, where a lateritic island seems to have been phosphatized at a fairly remote time. The history of this former island, which is evidently porous enough to permit significant variations in ground water level, may well be quite unlike that of the other localities. Apart from so-called colloidal aluminum phosphate, dufrenite, and harbortite, supposedly $6\text{Al}_2\text{O}_3 \cdot 4\text{P}_2\text{O}_5 \cdot 17\text{H}_2\text{O}$, occurred here, the latter possibly in part as pseudomorphs after pyrite.

EPIGEAN FORMATION OF TARANAKITE

The occurrences of aluminum phosphate off the coast of New Zealand are most instructive. Green and White Islets on the drier east coast have deposits of a material which is locally called Redonda phosphate (Morgan, 1915) and which may represent the most temperate occurrence of insular barrandite. On the much wetter west coast the conical islets of trachyte known as the Sugar Loaves, Taranaki, contained in fissures the cryptocrystalline potassium aluminophosphate which was described by Hector and Skey (1865) as taranakite. This mineral proves to be of rather widespread occurrence in caves, but is probably known in only one other epigeal guano deposit, namely, Isla Leones in Patagonia. The evidence available suggests that taranakite is characteristic of the phosphatization of aluminosilicate material in perennially wet localities. At Taranaki the taranakite was associated with vashegyite, a basic hydrated aluminum phosphate, essentially $4\text{Al}_2\text{O}_3 \cdot 3\text{P}_2\text{O}_5 \cdot 30\text{H}_2\text{O}$, otherwise not known associated with guano.

TABLE 56

	Epigeal Guano Deposits		Hypogean Guano Deposits		Hypogean Pleistocene Phosphate		Hypogean No Phosphate Source	
	I	II	III	IV	V	VI	VII	VIII
H ₂ O -	} 33.06%	31.71%	29.80%	7.87%	28.20%	28.73%	13.40%	9.49%
H ₂ O +				21.29			14.90	18.22
Al ₂ O ₃	21.43	20.67	21.00	22.89	18.59	21.60	18.18	20.59
Fe ₂ O ₃	4.45	0.86	2.90	1.17	0.83	0.50	—	0.19
FeO	tr.	—	—	—	—	—	—	—
K ₂ O	4.20	7.98	1.20	8.04	8.28*	7.00	5.80	8.95
(NH ₄) ₂ O	—	present	3.47	0.90	0.52	0.47	—	tr.
Na ₂ O	tr.	2.64	—	0.02	—	0.30	—	—
CaO	0.55	sl. tr.	—	tr.	1.40	0.00	0.31	tr.
MgO	—	tr.	—	tr.	0.33	—	tr.	tr.
P ₂ O ₅	35.05	32.47	42.70	37.10	37.28	40.40	35.17	40.85
SO ₃	tr.	—	—	—	tr.	—	tr.	—
Cl	0.46	—	—	—	tr.	—	tr.	—
F	—	—	—	—	tr.	—	tr.	—
SiO ₂ and insol.	0.80	3.67	—	0.36	4.35	0.54	11.60	1.10

I. Taranaki, taranakite.

II. Isla Leones.

III. Réunion.

IV. Monte Alburno.

V. Grotte de la Coquille ou Minerve (Carnot, 1895).

VI. The same (Gautier, 1914).

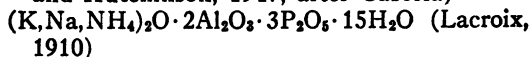
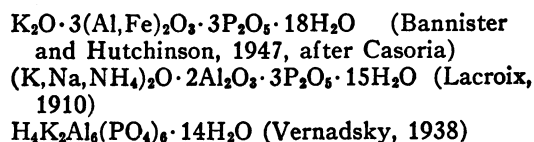
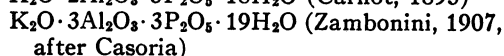
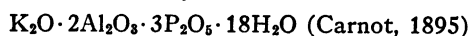
VII. Tour Combes, Misserghin, Oran, Algeria.

VIII. Jenolan Caves.

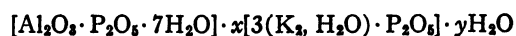
* Includes Rb, possibly about 0.1%; Pb present (Bannister and Hutchinson, 1947).

HYPOGEAN FORMATION OF TARANAKITE
AND OTHER ALUMINUM PHOSPHATES

The analyses of the various minerals that have been referred to minervite and palmerite are set out in table 56. Type palmerite and minervite from the type locality are now known to be identical with taranakite (Bannister and Hutchinson, 1947). The Monte Alburno and Réunion occurrences were clearly due to the action of bat guano on the underlying rock. The Grotte de la Coquille ou Minerve contains later Pleistocene phosphate probably derived from bat guano; the Misserghin and Jenolan occurrences are unassociated with any obvious source of phosphate, but the former existence of bat guano in these caves is much the most reasonable explanation of the origin of the material. A number of formulas have been proposed, namely:



It is evident that considerable variation in composition is possible within the limits set by the structure of the mineral. Gautier (1914) considered that the variation could be expressed by a formula of the following nature:



with the further possibility of substitution of some Al by Fe and some K by NH₄. Gautier concluded that for the original minervite of 1893 $x=4$, $y=2$, K₂:H₂ in second bracket as 2:1; later minervite of 1914 $x=7$, $y=1$, K₂:H₂ in second bracket as 1:1; Réunion and Tour Combes $x=6$, $y=0$, K₂:H₂ in second bracket as 2:1. It does not seem possible to reconcile the composition of the original

taranakite with Gautier's scheme. It is evident that Gautier's later sample from the Grotte de la Coquille is less basic than the original one, and extremely interesting to find that it took up potassium from KOH solution, the amount involved being equivalent to 3.5% of the P_2O_5 present, while to saturate the material with potassium would, according to Gautier's formula, be equivalent to neutralizing 4.65% of the total P_2O_5 . Bannister and Hutchinson, using minervite probably collected with the original material, obtained no evidence of exchange of NH_4^+ from ammonium chloride for either potassium or hydrogen. It is evident that the potassium is not reversibly exchangeable in the strict sense, though it would seem probable that at least part of the potassium occupies positions which can also be taken by hydrogen. Bannister and Hutchinson noted more than minute spectrographic traces of rubidium in the specimen from the Grotte de la Coquille which they examined. The quantity was evidently of the order to be expected in the lithosphere, but probably much greater than in the biosphere. It is therefore probable that the potassium, and with it the rubidium of the sample, were derived from the substrate with the aluminum and not from the guano solution that provided the phosphate. They also detected lead spectroscopically and suspected the presence of the element was due to contamination. Carnot, however, detected both lead and zinc in the bones of *Ursus spelaeus* from the locality; minute amounts of Pb^{++} ($r=1.32\text{\AA}$) may conceivably replace K^+ ($r=1.33\text{\AA}$) in the mineral. Li, Sr, Mn, and Zn appeared absent, but the conditions for recognition of the last-named element were poor.

A final aspect of taranakite must be briefly mentioned. If the mineral is the typical product of phosphatization of aluminosilicate rocks or their decomposition products under perennially wet conditions it is reasonable to look for its occurrence in other environments. In particular, as Bannister and Hutchinson point out, it may be formed in small quantities in damp soils. The possibility of the formation of the mineral should be borne in mind by pedologists interested in the fate of potassium and phosphate in temperate soils.

In addition to taranakite, other aluminum phosphates have been recorded in bat caves, but the accounts are in general inadequate. Barrandite seems to have occurred in the Tunnel du Cormoran, Réunion, but its genetic relations to the taranakite found at that locality are not clear from Lacroix's (1936) account. Variscite is stated to have occurred in the Drachenhöhle, Mixnitz; though the identification is not certain, the occurrence probably does not involve taranakite. The material occurred in the sandy layer under the chiropterite; aluminum is considerably enriched over iron in the supposed variscite. The evidence of the downward movement of aluminum phosphate in the Puerto Rican cave, Ancones, San German, suggests that a separation of aluminum from ferric phosphate owing to the somewhat greater solubility of the former is of fairly general occurrence, and Elschner thought the same process was at work at the surface of Necker Island. The nature of the aluminum phosphate in the Puerto Rican cave is quite unknown. No further interpretation of the analyses, other than those of taranakite, of material from the Jenolan Cave, New South Wales, is possible.

The last and most interesting of the problematic hypogean aluminum phosphates is that discovered by Marchand (1918) in bat guano in a cave near Ermelo. Analysis of the purest material gave:

Al_2O_3	19.24%	molecular ratio:	0.502
P_2O_5	53.58		1.000
H_2O	27.16		4.019

corresponding very closely indeed to an acid phosphate $Al_2O_3 \cdot 2P_2O_5 \cdot 8H_2O$ or $(AlPO_4 \cdot H_3PO_4)_2 \cdot 5H_2O$. On treatment with ammonia half the phosphate is dissolved and $AlPO_4$ presumably formed. In another sample part of the aluminum was replaced by iron. This material cannot be a taranakite in which all the potassium is replaced by hydrogen, as all the specimens of taranakite contain much more aluminum relative to phosphorus. The occurrence of this acid phosphate is most interesting, perhaps indicating how a hypogean phosphatization would occur in the absence of potassium. It is unfortunate that the Ermelo mineral is so little known.

SUMMARY OF PREVIOUSLY UNRECOGNIZED CONCLUSIONS

1. THE MAXIMUM RATE of deposition of nitrogenous guano on the western coasts of the continents in dry subtropical latitudes is of the order of 190,000 metric tons per annum, equivalent to about 8800 metric tons of phosphorous. The deposition as phosphatic guano on islands in other parts of the tropical and subtropical oceans is certainly not likely to exceed this figure, and for both processes together a mean figure of 10,000 tons of phosphorus removed, with limits of about 5000 and 15,000 tons, seems reasonable. The total rate of removal of phosphorus from sea to land by all the sea birds of the world is clearly of the order of $n.10^4$ to $n.10^5$ tons per annum, certainly not more than a few per cent of the rate of entry of phosphorus from the land to the sea by chemical erosion, which is of the order of 10^7 tons per annum.

2. The old deposits that had accumulated under existing bird colonies on the Peruvian coast, notably at the Chincha Islands, Guañape Island, Macabí Island, and the smaller Lobos Islands which were exploited during the nineteenth century, were probably all formed mainly from the excreta of *Phalacrocorax bougainvillei* and perhaps of *Sula variegata*. It seems probable that a change in the avifauna of the Chincha Islands occurred early in the nineteenth century, which led to a replacement of *P. bougainvillei* by *Pelecanoides garnotii*; there is some evidence that the latter bird was destroying rather than creating the deposits.

3. The initiation of the deposits on the islands named in the previous paragraph probably occurred in the first or second millennium B.C. It is believed that prior to that time climatic conditions were unsuitable for guano production or the persistence of any deposits that might have been produced. It is probable that the deposits on the coast of South West Africa also started to form in the geologically very recent past.

4. The evidence relating to abnormal climatic events, particularly with reference to a seven-year cycle in the inshore movement of warm water and the consequent biological catastrophes on the Peruvian coast, is reviewed in detail. The cycle was certainly well marked between 1864 and 1939, but prior to

this period there is no evidence of a seven-year cycle. The cycle is believed to be non-persistent, as many meteorological cycles are known to be. The best photograph of the stratification of old guano on Central Chincha Island shows what are probably annual varves, but no trace of a seven-year periodicity. Phenomena comparable to those of the abnormal years occur on the west coast of South Africa, but are obscured by other unrelated events. It is just possible that the South African abnormal years regularly antedate the Peruvian by one or two years.

5. There is some historic evidence which suggests that changes occur in the position of regions of maximum guano production on the Peruvian coast. The southern part of the coast and the coast of northern Chile have certainly declined in importance since the eighteenth century. Slight changes in the hydrographic pattern of the Peru Coastal Current may be involved.

6. The guano deposits of Chile are mainly post-Pleistocene but certainly older than the Peruvian deposits. It is supposed that the Chilean coast was climatically suitable for guano production at a time when the Peruvian coast was not. A slight fall in sea level has reduced the insularity of the Chilean coast, while at the same time the Peruvian coast has become dry enough to permit accumulation of nitrogenous guano.

7. The only important diagenetic change known in old unleached Peruvian guano is the practically quantitative formation of ammonium oxalate from uric acid. Decomposition and leaching of guano tend to produce a series of products in which the nitrogen decreases linearly with increasing phosphorus; wide departures from linearity are apparently due to contaminants. Most ancient Chilean samples show such departures, due largely to salt of marine origin.

8. The best-established crystalline minerals of Peruvian guano were taylorite, an anhydrous potassium ammonium sodium sulphate, and oxammite, ammonium oxalate monohydrate. It is possible that in pseudomorphs after birds' eggs some hydrated sulphates comparable to lecontite may have occurred.

9. There is evidence from the probable food intake and the amount of guano produced by *Phalacrocorax bougainvillei* in nature that the excreta are largely retained and deposited on the breeding ground. It is suggested that this behavior may characterize the more productive species of guano birds.

10. The slightly elevated atolls of the Pacific that had bird colonies and that bore over 10,000 metric tons of phosphatic guano all lay in a relatively restricted area of low rainfall and fairly high biological productivity, centered about latitude 2° S. The zone of high productivity, which corresponds to the old whaling ground "On the Line," is correlated with upwelling on the southern edge of the Southern Equatorial Current.

11. North and south of the region indicated in the previous paragraph, evidence of former guano production is forthcoming. In the western Pacific such evidence is very widespread, and a similar phenomenon appears to be exhibited by islands in the China Sea and the Caribbean, if not elsewhere. Either a shifting of the climatic and oceanographic zonation or a post-Pleistocene dry period seems to be indicated, but the evidence is inadequate to distinguish between the two hypotheses. The hypothesis of a shift in zonation would, however, accord with the Peruvian findings.

12. Old, much-elevated oceanic coral islands can bear deposits of phosphate in excess of anything produced in historic times, exceeding even the deposits of the Peruvian coast. It is probable that the phosphate on these islands is of Pleistocene date and that phosphatization is as characteristic of that period as is glaciation.

13. The Pleistocene deposits nearly always occupy the cavities of a Karrenfeld, comparable to the champignon of Aldabra, which may contain terra rossa but which in the most impressive cases (Nauru, Ocean Island, Makatea, lower terrace at Navassa) has evidently been washed clean of such residual material by resubmergence. The coral rock of these islands is usually dolomitized. It is most unlikely that the largest deposits could have formed under modern conditions of biological productivity. It is suggested that they represent the results of vastly increased

productivity correlated with changes in oceanic circulation as glacial and interglacial periods succeeded one another.

14. The deposits of bat guano of the world are considered; some of the largest are of Riss-Würm interglacial date, but no general significance is attached to this fact. The process of decomposition in bat guanos in such localities normally leads to loss of nitrogen. The last nitrogen is usually present as nitrate. This is in accord with bacteriological and geochemical expectations.

15. All excretory products that accumulate as guano tend, as decomposition and leaching occur, towards fluor-hydroxyl-carbonate-apatite (francolite); the quantity of fluorine present is variable. The distribution of fluorine urgently requires investigation, particularly on the elevated phosphatic islands. No theory of the source of the fluorine is without objection, and a solution of the problem might lead to conclusions of great interest.

16. Of the elements that might be present in the apatite formed from guano deposits, manganese is notably rare; it often occurs as oxide in association with such deposits. The redox potential of the biosphere is probably usually too high to permit an appreciable concentration of Mn^{++} .

17. Magnesium guano minerals probably are formed only where there is an extraneous source of magnesium either from sea water or from decomposing rock. Under highly ammoniacal conditions struvite is formed; in the absence of ammonia, newberyite and bobierite. The various ammonium magnesium phosphates of the Shipton Cave must represent narrowly defined intermediate conditions in ammonia concentration and perhaps water content.

18. Lacroix's view that in regions of seasonal tropical rainfall the phosphatization of any igneous rock leads to minerals of the form $(Al,Fe)PO_4 \cdot 2H_2O$ is in general confirmed. The hydrated potassium aluminum phosphate taranakite (=minervite, palmerite) seems to be characteristic of perennially damp localities such as caves both tropical and temperate, and bird colonies in temperate latitudes, as New Zealand and Patagonia. It should be considered as a possible soil constituent.

BIBLIOGRAPHY

- ABEL, O., AND G. KYRLE
1931. Die Drachenhöhle bei Mixnitz. Vienna (Verlag), Österr. Staatsdruckerei, Spelaeol. Monogr., vols. 7, 8.
- ACOSTA, JOSEPH DE
1940. Historia natural y moral de las Indias. Mexico, Fonda de cultura economica, lxxxv+638 pp.
Reprint; original edition, 1591.
- ADRIANCE, D., P. S. TILSON, AND H. H. HARRINGTON
1895. Miscellaneous analysis. Texas Agr. Exp. Sta., bull. 35, pp. 595-606.
- AGASSIZ, A.
1903. Reports on the scientific results of the expedition to the tropical Pacific by the U. S. Fish Commission steamer "Albatross" from August 1899 to March 1900. IV. The coral reefs of the tropical Pacific. Mem. Mus. Comp. Zool., vol. 28, 410 pp.
- AGÉTON, C. N.
1915. The origin, composition and fertilizer value of the bat guanos of Cuba and the Isle of Pines. Modern Cuba, vol. 3, no. 2, pp. 48-59.
1917. Guano de murciélago en Cuba. Cuba Estacion Exp. Agr., bull. 36.
- AGUERREVERE, S. E., AND V. M. LÓPEZ
1938. The geology of the island Gran Roque (Federal Dependency, Venezuela) and its phosphate deposits. Bol. Geol. y Min., Caracas (edition in English), vol. 2, nos. 2, 3, 4, pp. 151-180.
- AIKMAN, C. M.
1894. Johnston's elements of agricultural chemistry. From the edition of Sir Charles A. Cameron, revised and in great part rewritten by C. M. Aikman, 17th ed. Edinburgh and London, William Blackwood and Sons, 482 pp.
- ALBRECHT, A.
1921. Bat guano and its fertilizing value. Univ. Missouri Agr. Exp. Sta., bull. 180, 15 pp.
- ALEXANDER, W. B.
1928. Birds of the ocean. New York and London, G. P. Putnam's Sons, 428 pp.
- ALLISON, VERNON C.
1937. Evening bat flight from Carlsbad Caverns. Jour. Mammal., vol. 18, pp. 80-82.
- AMADON, DEAN
1942. Birds collected during the Whitney South Sea expedition. L. Notes on some non-passerine genera. 2. Amer. Mus. Novitates, no. 1176, pp. 1-21.
- AMERICAN GUANO COMPANY
1857. Report to stockholders of the American Guano Company. Brooklyn, New York, Jacobs and Brockway.
1859. Report of experiments with American guano. New York, W. H. Arthur and Co., 27 pp.
- AMPOLA, G.
1901. Il guano dell' Eritrea. Staz. Sperim. Agrarie Italiane, vol. 34, pp. 54-59.
- ANDERSON, G. M., AND B. ANDERSON
1936. The Cat Island gannet rookery. Emu, vol. 35, pp. 333-334.
- ANDERSON, THOMAS
1855. Proceedings in the laboratory: Composition of some new varieties of guano. Trans. Highland Soc., new ser., 1855-1857, pp. 56-58.
1857. Proceedings in the laboratory: On a deposit from a cave. *Ibid.*, new ser., 1855-1857, pp. 495-496.
1858. Proceedings in the laboratory: On the composition of some kinds of guano now in the market. *Ibid.*, new ser., 1857-1859, pp. 351-356.
1859. Proceedings in the laboratory: On some new varieties of guano. *Ibid.*, new ser., 1857-1859, pp. 485-490.
1861. Notes on some varieties of guano. *Ibid.*, new ser., 1859-1861, pp. 382-386.
1873. Proceedings in the laboratory: Composition of some of the kinds of guano now in the market. *Ibid.*, new ser., 1873, pp. 316-326.
- ANDERSSON, K. J.
1861. The Okavango River: a narrative of travel, exploration and adventure. London, Hurst and Blackett, 364 pp.
1872. Notes on the birds of Damara Land and the adjacent countries of southwest Africa. Edited by J. H. Gurney. London, J. van Voorst, 394 pp.
- ANDOUARD, A.
1894. Le phosphate du Grand-Connétable. Compt. Rendus Acad. Sci., Paris, vol. 119, p. 1011.
- ANDREWS, C. W.
1900. A monograph of Christmas Island. London, British Museum (Natural History), History and physical features, pp. 1-21; Geology, pp. 269-298.
- ANON.
1845a. The guano trade. (From the Shipping Gazette.) Nautical Mag., vol. 14, p. 53.
1845b. Guano islands. *Ibid.*, vol. 14, pp. 528-529.

- 1845c. Scotch guano. *Amer. Agriculturalist*, vol. 2, p. 251.
1847. Peruvian and African guano. *Ibid.*, vol. 4, pp. 108-109.
1858. Meeting of shipmasters at Kooria Moorla Islands. *Nautical Mag.*, vol. 27, pp. 222-223.
1861. Ueber Baker, Jarvis und Howland guano (Schluss). *Chem. Zentralbl.*, pp. 274-279.
- Drysdale analyses.
1863. The Chincha Islands (based on information obtained by Frederick Blumé and M. D. Rucker in 1862). *Illustrated London News*, vol. 42, pp. 200-201, fig. on p. 197.
1866. Eine seltene Mumie. *Globus*, vol. 9, p. 256.
1869. Die Chincha-Inseln an der peruanischen Küste. *Ibid.*, vol. 15, pp. 80-82.
1872. [Report of survey of guano deposits on the Lobos Islands.] *Nature*, vol. 5, "Notes" sect., p. 191.
1876. Guano auf den Bahama Inseln. *Globus*, vol. 29, p. 352.
1908. The development of the resources of the Seychelles. *Bull. Imp. Inst.*, London, vol. 6, pp. 107-126.
1911. Guano deposits of Assumption Island, Seychelles. *Ibid.*, vol. 9, pp. 39-44.
1914. Penguin guano from the Falkland Islands. *Ibid.*, vol. 12, pp. 208-210.
1920. Guano from Latham Island near Zan-zibar. *Ibid.*, vol. 18, pp. 189-191.
1928. Phosphate in Barbuda. *Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates*, vol. 2, pp. 785-786.
1936. Fledermaus-Guano aus Ostafrika. *Tropenpflanzer*, vol. 39, p. 449.
- 1945a. Estudio de la solubilidad en el agua de nitrógeno del guano. *Bol. Compañía Administradora Guano, Lima*, vol. 21, pp. 74-76.
- 1945b. Islas y puntas guaneras de la costa del Perú. *Ibid.*, vol. 21, pp. 142-148.
- 1945c. Speck. *New Yorker Mag.*, Dec. 1, 1945, pp. 28-29.
1947. Twenty million pets. *Time Mag.*, Sept. 15, vol. 50, no. 11, p. 67.
- ANTHONY, A. W.
- 1898a. Avifauna of the Revillagigedo Islands. *Auk*, vol. 15, pp. 311-318.
- 1898b. The boobys of the Revillagigedo Islands. *Osprey*, vol. 3, pp. 3-6.
1900. Nesting habits of the Pacific coast species of the genus *Ruffinus* [sic]. *Auk*, vol. 17, pp. 247-252.
- ANTHONY, H. E.
1919. Mammals collected in eastern Cuba in 1917. *Bull. Amer. Mus. Nat. Hist.*, vol. 41, pp. 625-643.
- 1925-1926. Mammals of Porto Rico, living and extinct. *New York Acad. Sci., Scientific Survey of Porto Rico and the Virgin Islands*, vol. 9, pp. 1-238.
- ARANCIBO, C. R.
1938. Las guaneras de Chile. *Bol. Min. Soc. Nac. Minera, Santiago de Chile*, vol. 50, pp. 211-214.
- ARCHER, SIR GEOFFREY F., AND E. M. GODMAN
1937. The birds of British Somaliland and the Gulf of Aden, their life histories, breeding habits and eggs. *London, Gurney and Jackson*, vol. 1, 285 pp.; vol. 2, 625 pp.
- ARUNDEL, JOHN T.
1890. The Phoenix groups and other islands of the Pacific. Read before the Geographical Society of the Pacific . . . San Francisco, 3rd March 1885, the notes added being information up to the date of reprint in the "New Zealand Herald," Auckland, July 5 and 12, 1890.
- ASO, YAWATA
1940. Phosphates. Tokyo, Maruzen Co., 209 pp.
- Translation made for the United States Navy, translation no. 399, April 22, 1946.
- ASTON, B. C.
1909. The soils and soil-formers of the Subantarctic Islands. In Chilton, C., *The Subantarctic Islands of New Zealand. New Zealand, The Philosophical Institute of Canterbury*, vol. 2, art. 31, pp. 745-777.
- BAILEY, G. E.
1902. The saline deposits of California. *Bull. California State Mining Bur.*, no. 24.
- BAILEY, H. H.
1906. Ornithological notes from western Mexico and the Tres Marias and Isabella Islands. *Auk*, vol. 23, pp. 369-391.
- BAILEY, THOMAS L.
1918. Report on the caves of the Eastern Highland Rim and Cumberland Mountains. *The Resources of Tennessee, State Geol. Survey*, vol. 8, no. 2, pp. 85-148.
- BAILEY, VERNON
1928. Animal life of the Carlsbad Cavern. *Monogr. Amer. Soc. Mammal.*, no. 3, Baltimore, Williams and Wilkins, 195 pp.
1931. Mammals of New Mexico. *North Amer.*

- Fauna, no. 53, Washington, D. C., U. S. Dept. Agr., Bur. Biol. Surv., 412 pp.
- BAKER, E. C. STUART
1929. The fauna of British India, including Ceylon and Burma. London, Taylor and Francis, Birds, second edition, vol. 6, 499 pp.
- BALDWIN, P. H.
1947. The Laysan rail. *Condor*, vol. 49, no. 1, pp. 14-21.
- BANNERMAN, DAVID
1928. Description of a new frigate-bird (*Fregata magnificens lowei*) from the Cape Verde Islands. *Bull. Brit. Ornith. Club*, vol. 48, p. 12.
- BANNISTER, F. A., AND H. BENNETT
1947. Whitlockite from Sebdou, Oran, Algeria. *Min. Mag.*, vol. 28, pp. 29-30.
- BANNISTER, F. A., AND G. E. HUTCHINSON
1947. The identity of minervite and palmerite with taranakite. *Min. Mag.*, vol. 28, pp. 31-35.
- BARKER, H. A.
1943. *Streptococcus allantoicus* and the fermentation of allantoin. *Jour. Bact.*, vol. 46, pp. 251-259.
- BARKER, H. A., AND J. V. BECK
1941. The fermentative decomposition of purines by *Clostridium acidi-urici* and *Clostridium cylindrosporum*. *Jour. Biol. Chem.*, vol. 141, pp. 3-27.
1942. *Clostridium acidi-urici* and *Clostridium cylindrosporum*, organisms fermenting uric acid and some other purines. *Jour. Bact.*, vol. 43, pp. 291-304.
- BARNES, J.
1817. A tour through the island of St. Helena, with notices of its geology, mineralogy, botany, etc. London, J. M. Richardson, 239 pp.
- BARNÉS, VENTURA, JR.
1946. The birds of Mona Island, Puerto Rico. *Auk*, vol. 63, pp. 318-327.
- BARRAL
1875. [Analysis.] *Jour. d'Agr.*, vol. 1, pp. 148-149, 307.
Not seen; *abstract in* Jahresber. Agr. Chemie.
- BARRÈRE, PIERRE
1743. Nouvelle relation de la France équinoxiale, contenant la description des cotes de la Guiane: de l'isle de Cayenne; le commerce de cette colonie; les divers changemens arrivés dans ce pays; et les moeurs et coutumes des différens peuples sauvage qui l'habitent. Paris, Piget, 250 pp.
- BARRETT-HAMILTON, GERALD E. H.
1911. A history of British mammals. London, Gurney and Jackson, pt. 4.
Reference to Kent's Cavern, p. 26.
- BASADRE, JORGE
1940. Historia de la República del Perú. Segunda edicion. Lima, Chorrillos, Talleres gráficos de la Escuela militar de Chorrillos, 476 pp.
- BASSETT, HENRY
1917. The phosphates of calcium. IV. The basic phosphates. *Jour. Chem. Soc.*, London, vol. 111, pp. 620-642.
- BAUDRIMONT, A.
1873. Observations sur la composition des guanos, sur les altérations qu'ils subissent et sur l'origine probable des phosphates fossiles de la région du Lot. *Compt. Rendus Acad. Sci.*, Paris, pp. 645-646.
- BEATSON, ALEXANDER
1816. Tracts relative to the island of St. Helena: written during a residence of five years. London, W. Bulmer and Co., 330 pp.
- BECK, R. H.
1921. Visiting the nests of seabirds by automobile. *Nat. Hist.*, vol. 21, pp. 399-407.
- BECKE, L.
1897. Wild life in southern seas. London, T. Fisher Unwin, 369 pp.
- BEEBE, C. WILLIAM
1924. Galapagos, world's end. New York and London, G. P. Putnam's Sons, 443 pp.
- BEHM, E.
1859. Das Amerikanische Polynesien und die politischen Verhältnisse in den übrigen Theilen des grossen Oceans im Jahr 1859. *Petermann's Mitth. for 1859*, pp. 173-194.
- BENNETT, F. D.
1840. Narrative of a whaling voyage around the globe. [Part on Caroline Island.] *Reprinted in* Bryan, E. H., Jr., *Paradise of the Pacific*, 1939, vol. 51, no. 11, pp. 19-21.
See Bryan, E. H., Jr., 1939b.
- BENT, ARTHUR C.
1922. Life histories of North American petrels and pelicans and their allies. *Bull. U. S. Natl. Mus.*, no. 121, 343 pp.
- BERTELS, C.
1843. Chemische Untersuchung des Guano. *Jour. prakt. Chem. (Erdmann and Marchand)*, vol. 28, pp. 5-16.
- BIEREMA, S.
1909. Die Assimilation von Ammon-, Nitrat, und Amidstickstoff durch Mikroor-

- ganismen. *Centralb. für Bakt.*, ser. 2, vol. 23, pp. 672-726.
- BINAGHI, RINALDO
1909. Contributo allo studio dei guani sardi con speciale riguardo alla determinazione dell' azoto ammoniacale. *Staz. Sperim. Agrarie Italiane*, vol. 42, pp. 195-230.
- BIRD, J. B.
1943. Excavations in northern Chile. *Anthrop. Papers Amer. Mus. Nat. Hist.*, vol. 38, pt. 4, pp. 173-318.
- BLACKWELDER, E.
1925. Phosphate deposits of the Pacific. *Econ. Geol.*, vol. 20, pp. 698-699.
- BLATCHLEY, W. S.
1897. Indiana caves and their fauna. *State of Indiana, Dept. Geol. and Nat. Resources*, 21st Ann. Rept. (1896), pp. 121-212.
- BLOFELD, J. H.
1852. Notes on St. Helena. *Quart. Jour. Geol. Soc. London*, vol. 8, pp. 195-196.
- BOBIERRE, A.
1868. Note sur le guano de Mexillones. *Comptes Rendus Acad. Sci.*, Paris, vol. 66, pp. 543-547.
- BÖHNECKE, G.
1936. Atlas zur: Temperatur, Salzgehalt und Dichte an der Oberfläche des Atlantischen Ozeans. In Defant, Albert, *Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition . . . "Meteor"* 1925-1927. Band V. Berlin and Leipzig, Walter de Gruyter u. Co.
- BOGGS, S. W.
1938. American contributions to geographical knowledge of the central Pacific. *Geogr. Rev.*, vol. 28, pp. 177-192.
- BOHNE, WILHELM
1926. Die Insel Nauru als Typus eines koralogenen Phosphatlagers. *Petermann's Mitth.*, vol. 72, pp. 52-59.
- BOLLAERT, W.
1859. [Carved stone found on the Chinchu or Guano Islands.] *Illustrated Times*, London, vol. 8, p. 157.
- BOLLE, C.
1855. Guano an der Küste Westafrikas. *Jour. für Ornith.*, vol. 3, p. 270.
- BORNEMANN-STARYNKENVITCH, I. D.
1938. On some isomorphic substitutions in apatite. *Comptes Rendus (Doklady) Acad. Sci. URSS*, new ser., vol. 19, pp. 253-255.
- BOULE, MARCELLIN
1906. Les grottes de Grimaldi (Baoussé-Roussé). *Monaco, Géol. et Paléont.*, vol. 1, no. 2 pp. 73-156.
- BOUSSINGAULT, P.
1860a. Sur la présence des nitrates dans le guano. *Compt. Rendus Acad. Sci.*, Paris, vol. 50, pp. 887-890.
1860b. Fragments d'un mémoire sur les gisements du guano dans les îlots et sur les côtes de l'océan Pacifique. *Ibid.*, vol. 51, pp. 844-855.
- BOWMAN, ISAIAH
1916. The Andes of southern Peru: geographical reconnaissance along the seventy-third meridian. New York, published for the American Geographical Society, Henry Holt and Co., 336 pp.
- BOYD, A. J.
1893. Reminiscences of the Chinchu Islands. *Proc. and Trans. Queensland Branch Roy. Geogr. Soc. Australasia*, vol. 8, pp. 3-12.
- BRAND, DONALD D.
1937. The natural landscape of northwestern Chihuahua. *Univ. New Mexico Bull.*, whole ser., no. 316, geol. ser., vol. 5, no. 2, 74 pp.
- BRANDT, F.
1932. Ein neuer Typ von Eisen-Tonerdephosphat-Vorkommen (Maranhao, Nordbrasilien). *Chemie der Erde*, vol. 7, pp. 383-425.
- BRANNER, JOHN CASPER
1919. Outlines of the geology of Brazil to accompany the geologic map of Brazil. *Bull. Geol. Soc. Amer.*, vol. 30, pp. 189-338.
- BRASSEUR, H., M. J. DALLEMAGNE, AND J. MÉLON
1946. The chemical nature of salts from bones and teeth and of tricalcium phosphate precipitates. *Nature*, London, vol. 157, p. 453.
- BRAUN
1896. Untersuchungen über den Fluorgehalt von Phosphaten, Superphosphaten, Knochenmehlen und Guanosen. *Chem. Indust.*, Berlin, vol. 19, pp. 181-185.
- BREHM, A.
1870. Vogelfauna des Rothen Meeres. *Jour. für Ornith.*, vol. 18, p. 156.
- BRONGERSMA-SANDERS, MARGARETHA
1948. The importance of upwelling water to vertebrate paleontology and oil geology. *Verhandel. k. Nederlandisch Akad. Wetensch.*, Aft. Natuurk., ser. 2, vol. 45, pp. 1-112.
- BROOKS, C. E. P.
1920. The climate and weather of the Falkland Islands and South Georgia. Lon-

- don, Great Britain Met. Office, Geophys. Mem., no. 15, pp. 97-146.
- BROWN, H. H.
1942. The sea fisheries of Barbados. Development and Welfare in the West Indies, bull. 1, 32 pp.
- BRÜGGEN, J.
1938. Geología de las guaneras de Chile. Rev. Chilena Hist. y Geogr., vol. 85, pp. 172-210.
1939a. Geología de las guaneras de Chile. *Ibid.*, vol. 86, pp. 115-138.
1939b. Guano-Studien I: Bildung und Gewinnung des Guanos in Chile und Peru. Natur und Volk (Senckenbergische Naturforschende Gesellsch.), vol. 69, pp. 179-186.
1939c. Guano-Studien II: Guano-lager in Chile. *Ibid.*, vol. 69, pp. 239-249.
- BRUN, PIERRE DE
1900. Essai de minerologie du departement du Gard. Nîmes Bull. Soc. Étude Sci. Nat., vol. 28, pp. 88-137.
- BRYAN, E. H. JR.
1939a. What were the Guano Islands? Paradise of the Pacific, vol. 51, no. 9, pp. 5-7; no. 10, pp. 18-20.
1939b. Bennett's description of Caroline Island. *Ibid.*, vol. 51, no. 11, pp. 19-21.
1940. The noisy birds of Canton Island. *Ibid.*, vol. 52, no. 5, p. 20; no. 6, pp. 10, 19
1942. American Polynesia and the Hawaiian chain. Honolulu, Tongg Publishing Co., 253 pp.
- BRYAN, E. H., JR., AND COLLABORATORS
1926. Insects of Hawaii, Johnston Island and Wake Island. Bull. Bernice P. Bishop Mus., no. 31, Tanager expedition, publ. no. 3, 94 pp.
- BRYAN, W. A.
1903. A monograph of Marcus Island. Occas. Papers Bernice P. Bishop Mus., vol. 2, pp. 77-139.
1906. A report of a visit to Midway Island. *Ibid.*, vol. 2, pp. 291-299.
- BRYANT, W. E.
1889. A catalogue of the birds of Lower California. Proc. California Acad. Sci., ser. 2, vol. 2, pp. 237-320.
- BUCKLAND, WILLIAM
1822. Account of an assemblage of fossil teeth and bones of elephant, rhinoceros, hippopotamus, bear, tiger and hyaena, and sixteen other animals; discovered in a cave at Kirkdale, Yorkshire, in the year 1821: with a comparative view of five similar caverns in various parts of England, and others on the continent. Phil. Trans. Roy. Soc. London, vol. 112, pt. 1, pp. 171-237.
1823. Reliquae diluvianae: or observations on the organic remains contained in caves, fissures and diluvial gravel, and on other geological phenomena attesting the action of a universal deluge. London, John Murray, 303 pp.
- BUDDLE, G. A.
1938. Notes on the birds of Canton Island. Auckland Inst. and Mus. Rec., vol. 2, no. 3, pp. 125-132.
- BULLOUGH, W. S.
1942. Observations on the colonies of the arctic tern (*Sterna macrura* Naumann) on the Farne Islands. Proc. Zool. Soc. London, ser. A, vol. 112, pp. 1-12.
- BURT, C. E., AND M. D. BURT
1932. Herpetological results of the Whitney South Sea expedition. VI. Pacific island amphibians and reptiles in the collection of the American Museum of Natural History. Bull. Amer. Mus. Nat. Hist., vol. 63, pp. 461-597.
- BUZAGLO, H. F.
1930. Contribución al estudio de la composición del nitrógeno y ácido fosfórico en los guanos. Bol. Compañía Administradora Guano, Lima, vol. 6, pp. 407-413.
- BYRON, CAPT. THE RIGHT HON. LORD
1826. Voyage of H.M.S. Blonde to the Sandwich Islands, in the years 1824-1825. London, J. Murray, 260 pp.
- CABRERA, ANGEL
1914. Fauna ibérica: mamíferos. Madrid, Museo nacional de ciencias naturales, xviii+441 pp.
- CAMERON, F. K.
1912. A preliminary report on the fertilizer resources of the United States. Washington, D. C., Senate Document no. 190, 62d Congr., 2d session.
- CAMPBELL, ARCHIBALD J.
1901. Nests and eggs of Australian birds. Sheffield, Pawson and Brailsford, pt. 2.
- CAMPBELL, CHARLES A. R.
1925. Bats, mosquitoes and dollars. Boston, viii+262 pp.
- CANCINO, J. M.
1935. Guano del Perú. Bol. Soc. Química Peru, vol. 2, pp. 9-18.
1943. Analytical and industrial aspects of chromatography. Actas y Trabajos Congr. Peruano Quim., vol. 2, pp. 300-306.
Not seen; reference in Chem. Abstr., vol. 39, p. 3476.

- CAÑAS, FRANCISCO
1854. Exploracion de las islas de Chincha. Lima, Imprenta de la Patria, 36 pp., 3 maps.
- CARNE, J. E., AND M. MORRISON
1919. Phosphate deposits in limestone caverns in New South Wales. *Appendix 2 in* Carne, J. E., and L. J. Jones, The limestone deposits of New South Wales. Sydney, New South Wales Geological Survey, Mineral Resources no. 25.
Reports reprinted from Ann. Repts. Dept. Mines, New South Wales, for the years 1914 and 1917.
- CARNOT, A.
1895a. Sur un gisement de phosphates d'alumine et de potasse, trouvé en Algérie, et sur la genèse de ces minéraux. *Compt. Rendus Acad. Sci., Paris*, vol. 121, pp. 151-155.
1895b. Sur un gisement de phosphates d'alumine et de potasse, trouvé en Algérie, et sur la genèse de ces minéraux. *Ann. des Mines, Mem.*, ser. 9, vol. 8, pp. 311-320.
1896. Sur les variations observées dans la composition des phosphates. *Ibid.*, ser. 9, vol. 10, pp. 137-231.
- CARREY, E.
1875. Le Pérou; tableau descriptif, historique et analytique des êtres et des choses de ce pays. Paris, Garnier Frères, 511 pp.
- CARTENI, A., AND G. ALOJ
1934-1935. Composizione chimica di animali marini del golfo di Napoli. *Quaderni della Nutrizione*, vol. 1, pp. 49-63.
- CASORIA, EUGENIO
1904. Sopra un nuovo fosfato aluminico-potassico, idrato. *Atti Roy. Accad. Georgofili di Firenze*, vol. 82 (ser. 5, vol. 1), pp. 291-293.
- CASTAÑON, JOSE, FERMIN ASENCIOS, FRANCISCO CAÑAS, JOSE EBOLI, ANTONIO RAIMONDI, AND MANUEL J. SAN MARTIN
1854. [Report on survey of Central and South Chincha, pp. 43-50.] Informes sobre la existencia de huano en las Islas de Chincha presentados por la comision nombrada por el gobierno peruano. Lima, Tipographia de "El Heraldo," 52 pp.
- CASTELNAU, F. DE
1851. Expédition dans les parties centrales de l'Amérique du Sud. Paris, Bertrand, vol. 3, 483 pp.
- CASTERET, NORBERT
1938. Observations sur une colonie de chauves-souris migratrices. *Mammalia*, vol. 2, pp. 29-34.
1939. La colonie de murins de la grotte des Tignahustes. *Ibid.*, vol. 3, pp. 1-9.
- CATALANO, LUCIANO R.
1933. Informes sobre depositos de guano en dos islas de la costa Atlantica: depositos de guano en la isla Leones (Territoria del Chubut). Argentina Direc. Minas y Geol., no. 100, pp. 1-19.
- CHANDOS, DANE
1945. Village in the sun. New York, G. P. Putnam's Sons, 260 pp.
- CHAPIN, JAMES P.
1946. Wideawake Fair invaded. *Nat. Hist.*, vol. 55, no. 7, pp. 313-319.
- CHÉTELAT, E. DE
1938. Remarques sur l'île Alcatraz et sur quelques récits de la côte de la Guinée Française. *Rev. Géogr. Phys. et Géol. Dyn.*, vol. 11, pp. 145-149.
- CHEVRON, L.
1880. Guanos d'Australie. *Rev. Univ. des Mines*, ser. 2, vol. 7, pp. 437-444.
- CHRISTENSEN, E.
1947. Migration and hibernation of *Tadarida mexicana*. *Jour. Mammal.*, vol. 28, pp. 59-60.
- CHRISTOPHERSEN, E.
1927. Vegetation of Pacific equatorial islands. *Bull. Bernice P. Bishop Mus.*, no. 44, 79 pp.
1931. Vascular plants of Johnston and Wake Islands. *Occas. Papers Bernice P. Bishop Mus.*, vol. 9, no. 13, 20 pp.
- CHRISTOPHERSEN, E., AND E. L. CAUM
1931. Vascular plants of the Leeward Islands, Hawaii. *Bull. Bernice P. Bishop Mus.*, no. 81, 41 pp.
- CHU, T. O.
1929. The guano deposits of the Western Islands (Hsisatao) or Paracel Reefs. *Bull. Geol. Soc. China*, vol. 8, pp. 91-94.
- CHUBB, L. J.
1930. Geology of the Marquesas Islands. *Bull. Bernice P. Bishop Mus.*, no. 68, pp. 1-71.
- CIEZA DE LEON, PEDRO DE
1554. The travels of Pedro de Cieza de Leon, A.D. 1532-1550, contained in the first part of his Chronicle of Peru. Translated and edited by C. R. Markham. London, Hakluyt Society, 1864, 438 pp.
- CLARK, FRANCES N.
1940. The sardine: international aspects of its life history and exploitation. *Proc. Sixth Pacific Sci. Congr., Pacific Sci. Assoc.*, vol. 3, pp. 251-256.
- CLARK, J.
1882. The composition of some fossil eggs

- from the Peruvian guano deposits. Proc. Phil. Soc. Glasgow, vol. 15, pp. 573-575.
- CLASSEN, TH.
1930. Periodisches Fischsterben in Walvis Bay, South West Afrika. Palaeobiologica, vol. 3, pp. 1-13.
- CLAYTON, H. H.
1927. World weather records. Smithsonian Misc. Coll., vol. 79 (whole vol.), publ. no. 2913, 1199 pp.
- CLERGET, M.
1932. Contribution à l'étude des Îles Paracels. Les phosphates. Gouv. Gen. de l'Indochinie; Inst. Oceanographique de l'Indochinie, 20th note, 18 pp.
- CLOSSON, M. H.
1893. Under the Southern Cross. The Overland Monthly, ser. 2, vol. 21, pp. 205-216.
- COCKAYNE, L.
1909. The ecological botany of the Subantarctic Islands of New Zealand. In Chilton, C., The Subantarctic Islands of New Zealand. New Zealand, The Philosophical Institute of Canterbury, vol. 1, art. 10, pp. 182-235.
- COKER, R. E.
1919. Habits and economic relations of the guano birds of Peru. Proc. U. S. Natl. Mus., vol. 56, pp. 449-511.
1935. The protection of birds made profitable. Science, new ser., vol. 82, no. 2114, pp. 10-12.
- COLLINGWOOD, C.
1867. Ascension: Wide-awake Fair and the turtle ponds. Zoologist, ser. 2, 1867, pp. 979-984.
- COMPANHIA ADMINISTRADORA DEL GUANO, LIMA
1926. [No title.] Bóletin, vol. 2, no. 9, pp. 439-500.
1945. 36th Memoria del Directorio de la Compañia Administradora del Guano, correspondiente al año economica de 1944. *Ibid.*, vol. 21, no. 2, 63 pp.
- COOK, CAPT. JAMES
1785. A voyage to the Pacific ocean . . . 1776-1780. London, Printed by H. Hughs for G. Nicol and T. Cadell, 3 vols.
- COOKE, C. MONTAGUE, JR.
1934. Land shells of Makatea. Occas. Papers Bernice P. Bishop Mus., vol. 10, no. 11, 11 pp.
- COOKE, H. B. S.
1941. A preliminary survey of the Quaternary period in southern Africa. Union of South Africa, Dept. Interior Bur. Archaeol., archaeol. ser., no. 4, pp. 1-60.
- COOKE, WYTHE
1921. Stratigraphic and structural geology and geologic history. *Chapt. 4 in* Vaughan, T. W., W. Cooke, D. D. Condit, C. P. Ross, W. P. Woodring and F. C. Calkins, A geological reconnaissance of the Dominican Republic. Washington, United States Geological Survey, 268 pp.
- COOKSON, W. E.
1874a. Great Britain, Parliamentary Sessional Papers (1874b, *q.v.*), vol. 68, pp. 2-4. Also in French translation in Thierry, 1874.
1874b. Great Britain, Parliamentary Sessional Papers (1874c, *q.v.*), vol. 68, 3 pp.
1876. Great Britain, Parliamentary Sessional Papers (1876, *q.v.*), vol. 76, 3 pp.
- COOPER, L. H. N.
1937. The nitrogen cycle in the sea. Jour. Marine Biol. Assoc. United Kingdom, Plymouth, vol. 22, pp. 183-204.
- COPEMAN, P. R., AND F. J. DILLMAN
1937. Changes in the composition of guano during storage. Jour. Agr. Sci., vol. 27, pp. 178-187.
- COPENHAGEN, W. J.
1934. Occurrence of sulphides in certain areas of the sea bottom on the South African coast. Union of South Africa, Dept. Commerce and Industries, Fisheries and Marine Biol. Survey, rept. no. 11 for 1933, Investigational Rept., no. 3, 11 pp.
- COREAL, FRANCISCO
1722. Voyages de Francois Coreal aux Indes Occidentales. Amsterdam, J. F. Bernard, vol. 2, 278 pp. Arica, pp. 80-81.
- CORY, CHARLES B.
1909. The birds of the Leeward Islands, Caribbean Sea. Field Mus. Nat. Hist., ornith. ser., vol. 1, no. 5, pp. 193-255.
- COSTA SENA, J. C. DA
1883. Analyse do phosphato de cal da ilha Rata (Fernando de Noronha). Ann. Esc. Minas de Ouro Preto, no. 2, pp. 143-146.
- COUSINS, H. H.
1903. Local deposits of bat guano. Bull. Dept. Agr. Jamaica, vol. 1, pp. 144-146.
- COWARD, T. A.
1907. On the winter habits of the greater horseshoe, *Rhinolophus ferrum-equinum* (Schreber), and other cave-haunting bats. Proc. Zool. Soc. London, pp. 312-324.

- COX, ALVIN J.
1912. Philippine guano. *Philippine Jour. Sci.*, vol. 7A, pp. 195-199.
- COX, E. T.
1879. Eighth, ninth and tenth annual report of the Geological Survey of Indiana made during the years 1876-77-78. Indianapolis, Indianapolis Journal Co., 541 pp.
- COX, S. HERBERT
1883. Notes on the mineralogy of New Zealand. *Trans. and Proc. New Zealand Inst.*, vol. 15, pp. 361-409.
- CRAWLEY
1908. Fertilizers. *Estación Cent. Agr. Cuba* (English edition), bull. no. 14, 35 pp.
- CRICHTON, WM., AND SON
1868. Redonda Island guano. Report by David Stewart, M.D. Baltimore, J. Murphy and Co., 23 pp.
Trade pamphlet.
- CROIZET, J. B., AND A. C. B. JOBERT
1828. *Recherches sur les ossements fossiles du Département du Puy-de-Dôme*. Paris, 224 pp., 34 pls., maps and sections.
- CROWTHER, W. E. L. H.
1939. The development of the guano trade from Hobart Town in the fifties and sixties. *Papers and Proc. Roy. Soc. Tasmania*, for 1938, pp. 213-220.
- CUVIER, GEORGES
1835. *Recherches sur les ossements fossiles*. 4^{ème} edition. Paris, vol. 7, 533 pp.
- DAFERT, O., AND K. ENTRES
1931. Weitere Beiträge zur Kenntnis des Höhlendüngers. In Abel, O., and G. Kyrle, *Die Drachenhöhle bei Mixnitz*. Vienna, (Verlag) Osterr. Staatsdruckerei, Spelaeol. Monogr., vols. 7, 8, pp. 281-286.
- DAFERT, O., AND J. HÖFINGER
1931. Untersuchungen über die Löslichkeit der Phosphorsäure in Mixnitzer Höhlendünger. In Abel, O., and G. Kyrle, *Die Drachenhöhle bei Mixnitz*. Vienna, (Verlag) Osterr. Staatsdruckerei, Spelaeol. Monogr., vols. 7, 8, pp. 276-280.
- DALY, R. A.
1925. The geology of Ascension Island. *Proc. Amer. Acad. Arts and Sci.*, vol. 60, pp. 1-80.
1928. The geology of Saint Helena Island. *Ibid.*, vol. 62, pp. 31-92.
1934. *The changing world of the Ice Age*. New Haven, Yale University Press, 271 pp.
- DANA, J. D.
1852. On coral reefs and islands: Part eighth. *Amer. Jour. Sci.*, ser. 2, vol. 14, pp. 76-84.
1892. The system of mineralogy. Sixth edition by E. S. Dana. New York, J. Wiley and Sons, 1134 pp.
- DANCUART, P. E.
1903. Huano. *Anales de la Hacienda Pública del Perú*, Lima, Imprenta del estado, vol. 3, pp. 22-28.
1905. *Anales de la Hacienda Pública del Perú*. [Second edition.] Lima, Libreria e imprenta Gil, vol. 1, 290 pp.
1906. Huano. *Chapt. 5 in Anales de la Hacienda Pública del Perú*. Lima, vol. 8, 1869 and 1870, pp. 19-22.
- DARLING, FRANK FRASER
1938. Bird flocks and the breeding cycle: a contribution to the study of avian sociality. Cambridge, England, The University Press, 124 pp.
- DARWIN, C. R.
1844. Geological observations on the volcanic islands, visited during the voyage of H.M.S. "Beagle," together with some brief notices on the geology of Australia and the Cape of Good Hope. London, Smith, Elder and Co., 175 pp.
- DAVIS, W. M.
1926. The Lesser Antilles. *Amer. Geogr. Soc. Map of Hispanic America*, publ. no. 2, 207 pp.
- DAWKINS, W. BOYD
1874. Cave hunting. London, Macmillan and Co., xxiv+455 pp.
- DEFANT, A.
1936. Schichtung und Zirkulation des Atlantischen Ozeans. In Defant, Albert, *Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition . . . "Meteor" 1925-1927*. Band VI, Erster Teil. Berlin and Leipzig, Walter de Gruyter u. Co., pt. 3, Die Troposphäre des Atlantischen Ozeans, pp. 289-411.
- DELACOUR, J., AND E. MAYR
1945. The family Anatidae. *Wilson Bull.*, vol. 57, pp. 3-35.
- DELANO, AMASA
1817. A narrative of voyages and travels in the Northern and Southern Hemispheres. Boston, E. G. House, 598 pp.
- DE LA PROVOSTAYE, M.
1861. Note relative à la communication précédente sur les cristaux de phosphate ammoniac-magnésien du guano de carrière. *Compt. Rendus Acad. Sci.*, Paris, vol. 53, pp. 442-444.
- DELFORTRIE, M.
1871. Les gîtes de chaux phosphatée dans le Département du Lot; leur faune, le mode et l'époque probables de leur

- formation. Act. Soc. Linneene Bordeaux, vol. 28, pp. 505-518.
- DENHAM SMITH, J.
1845. On the composition of some varieties of South American guano; with the description of a new mode of estimating ammonia, and of a process for separating lime from magnesia, when these earths exist in combination with phosphoric acid. Mem. Proc. Chem. Soc. London, vol. 2, pp. 140-158.
- DETIENNE, E. G.
1880. Liege Sect. Assoc. Engineers, 25 July-5 Dec. 1880.
Not seen; *quoted in* Fallon, J. H. M., 1889, Jour. Soc. Chem. Indust., vol. 18, pp. 213-221.
- DICKSON, D.
1939. Hull Island. Paradise of the Pacific, vol. 51, no. 10, pp. 13-14.
- DIETZ, R. S., K. O. EMERY, AND F. P. SHEPARD
1942. Phosphorite deposits on the sea floor off southern California. Bull. Geol. Soc. Amer., vol. 53, pp. 815-847.
- DILL, H. R.
1912. Report on conditions on the Hawaiian bird reservation with a list of the birds found on Laysan. U. S. Dept. Agr., Biol. Survey Bull., no. 42, pp. 7-24.
- DIXON, W. A.
1878a. Notes on the meteorology and natural history of a guano island. Jour. and Proc. Roy. Soc. New South Wales, for 1877, vol. 11, pp. 165-175.
1878b. The guano and other phosphatic deposits occurring on Malden Island. *Ibid.*, for 1877, vol. 11, pp. 176-181.
- DIXON, W. S.
1884. Report of the Eclipse expedition to Caroline Island, May 1883. IV 6. Notes on the zoology of Caroline Island. Mem. Natl. Acad. Sci., vol. 2, pp. 90-92.
- DIXON, W. S., AND W. TRELEASE
1884. Report of the Eclipse expedition to Caroline Island, May 1883. IV 5. Botany of Caroline Island. Mem. Natl. Acad. Sci., vol. 2, pp. 87-90.
- DOMEYKO, I.
1874. Cuarto apéndice al Tratado de Mineralojía i reino mineral de Chile i de las republicas vecinas. An. Univ. Chile, vol. 45, pp. 99-153.
1878a. Sexto apéndice al Tratado de Mineralojía i al reino mineral de Chile i de las republicas vecinas. *Ibid.*, vol. 53, pp. 5-50.
1878b. Apuntes sobre el depósito de guano de Mejillones, sacados de las cartas es-
critas por el doctor don Guillermo Krull a los señores Villanueva i Domeyko. *Ibid.*, vol. 53, pp. 447-461.
1880. Sur les phosphates et les borophosphates de magnesie et de chaux provenant du dépôt de guano de Mejillones (lat. 23° à 24° S). Compt. Rendus Acad. Sci., Paris, vol. 90, pp. 544-547.
- DOMINICIS, A. DE
1919. Ricerche sopra i guani (Nuovi depositi di guani trovati in Sardegna). Ann. R. Scuola Superiore Agr. Portici, ser. 2, vol. 15, no. 18, 12 pp.
- DOOREN DE JONG, L. E. DEN
1929. Über *Bacillus fastidiosus*. Zentralbl. für Bakt., div. 2, vol. 79, pp. 344-353.
- DOUGLAS, G. VIBERT
1930. Topography and geology of the Tristan da Cunha group. In Report on the geological collections made during the voyage of the "Quest" on the Shackleton-Rowett expedition to the South Atlantic and Weddell Sea in 1921-1922. London, British Museum, pp. 67-71.
- DOVALINA, JOSÉ
1928. Existencias de minerales fosfatados en Méjico. Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates, vol. 2, pp. 787-806.
- DRYSDALE, ROBERT H.
1861. Ueber Baker- Jarvis- und Howland-Guano (Schluss). Chem. Centralbl., new ser., vol. 6, pp. 274-279.
Based on otherwise apparently unpublished material communicated by Drysdale. The first part of the paper relates to J. von Leibig's analyses.
- DUCLOS, M.
1928. Madagascar. Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates, vol. 2, pp. 591-595.
- DUDICH, E.
1925. Die ungarischen Fledermausfliegen. Math. termes. Ertes., vol. 41, pp. 144-151.
Not seen; reference from Wolf, 1934-1937.
- DUFFIELD, A. J.
1881. The prospects of Peru; the end of the guano age and a description thereof with some account of the guano deposits and "nitrate" plains. London, Newman and Co., 120 pp.
- DUNSTAN, B.
1928. Phosphates of Queensland. Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates, vol. 2, pp. 829-830.

- DUNSTAN, WYNDHAM R.
1905. Report on four samples of bat guano from the Federated Malay States. *Agr. Bull. Straits and Federated Malay States*, vol. 4, pp. 394-397.
- DUPONT, P. R.
1925. Seychelles guano deposits. *Jour. Fertilizers, Feeding Stuffs and Farm Supplies*, vol. 10, p. 214.
1928. Seychelles guano deposits. *Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates*, vol. 2, pp. 609-610.
- DUPOUY, GASTON
1913. *Études minéralogiques sur l'Indochine française*. Paris.
- DU TOIT, A. L.
1917. Report on the phosphates of Saldanha Bay. Union of South Africa, Dept. Mines and Industries, *Geol. Surv. Mem.*, no. 10, 38 pp.
- EDRISI
1154. *Géographie d'Édrisi* traduit par Jaubert. In *Recueil de voyages et de mémoires*. Paris, Société de Géographie, 1836, vol. 1.
- EGUIGÜREN, D. V.
1894. Las lluvias en piura. *Bol. Soc. Geogr. Lima*, vol. 4, nos. 7-9, pp. 241-248.
- EINBRODT, PAUL
1846. Notiz über die Zusammensetzung des Harnoxyds. *Ann. Chem. Pharm.*, vol. 58, pp. 15-18.
- EISENTRAUT, MARTIN
1936. Ergebnisse der Fledermausberingung nach drei jähriger Versuchzeit. *Zeitschr. Morph. Oekol. Tiere*, vol. 31, pp. 1-26.
- ELLIS, A. F.
1936. Ocean Island and Nauru; their story. Sydney, Australia, Angus and Robertson, 319 pp.
1937. *Adventuring in Coral Seas*. Second edition. Australia, Angus and Robertson, 264 pp.
- ELSCHNER, C.
1913. Corallogene Phosphat-Inseln Austral-Oceaniens und ihre Produkte. Lübeck, Max Schmidt, 120 pp.
1915. The Leeward Islands of the Hawaiian group. Honolulu, reprinted from the Sunday Advertiser, 68 pp.
1922. Kolloide Phosphate. *Kolloid-Zeitschr.*, vol. 31, pp. 94-96.
1923. Beiträge zur Kenntnis der Koralleninseln des Stillen Ozeans. *Zeitschr. prakt. Geol.*, vol. 31, pp. 69-73.
- EMORY, K. P.
1934. Archaeology of the Pacific equatorial islands. *Bull. Bernice P. Bishop Mus.*, no. 123, 43 pp.
1939. Additional notes on the archaeology of Fanning Island. *Occas. Papers Bernice P. Bishop Mus.*, vol. 15, no. 17, pp. 179-189.
- ERNST, A.
1884. La exposicion nacional de Venezuela en 1883. *Obra esenta de orden del ilustre americano General Guzman Blanco*. Caracas, Imprenta de la "Opinion Nacional," vol. 1, 704 pp.
Phosphatic guano, pp. 123-129.
- ESCHWEGE, W. L. VON
1833. *Pluto Brasiliensis*. Berlin, 491 pp.
- EVERETT, HART A.
1880. Report of the exploration of the caves of Borneo. Introductory remarks by John Evans and note on the bones collected by G. Bush. *Proc. Roy. Soc. London*, vol. 30, pp. 310-321.
- "EX-MEMBER OF THE COMMITTEE"
1845. The African guano trade. *Nautical Mag.*, 1845, enlarged ser. no. 11, pp. 619-666.
- FALCOZ, L.
1923. Biospéologica. XLIX. Pupipara (Diptères). 1^{re} ser. *Arch. Zool. Exper. Gen.*, vol. 61, pp. 521-552.
- FALLON, J. H. M.
1899. The Peruvian guano deposits from 1878 to 1898. *Jour. Soc. Chem. Indust.*, vol. 18, pp. 213-221.
- FARAGUET, C.
1854. Memoria sobre la cubicación del huano en la isla norte de Chíncha. In *Informes sobre la existencia de huano en las Islas de Chíncha* presentados por la comision nombrada por el gobierno peruano. Lima, Tipographia de "El Heraldo," pp. 36-42.
- FARQUHARSON, R. A.
1928. Occurrence of phosphoric minerals in British Somaliland. *Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates*, vol. 2, pp. 609-614.
- FEUILLÉE, LOUIS
1714. *Journal des observations physiques, mathématique et botaniques... 1707 jusques en 1712*. Paris, P. Giffart, vol. 2, 767 pp.
Arica, pp. 606-607.
- FIEDLER, REGINALD H., NORMAN D. JARVIS, AND MILTON J. LOBELL
1943. La pesca y las industrias pesqueras en el Perú. Lima, Compañía Administradora del Guano, 371 pp.

- FIEDLER, REGINALD H., MILTON J. LOBELL, AND C. R. LUCAS
 1943a. The fisheries and fishery resources of Honduras. A report of the Caribbean Fisheries Mission, U. S. Dept. Interior: Fish and Wild Life Service and the Office of the Coordinator of Inter-American Affairs, no. 9310, Washington, 10 pp.
 Mimeographed.
 1943b. The fisheries and fishery resources of Venezuela. As above, no. 9327, 30 pp.
 Mimeographed.
 1943c. The fish and fishery resources of the Caribbean area. As above, no. 9740, 60 pp.
 Mimeographed.
- FISHER, H. I., AND P. H. BALDWIN
 1946. War and the birds of Midway Atoll. Condor, vol. 48, pp. 1-15.
- FISHER, WALTER K.
 1903. Birds of Laysan and the Leeward Islands, Hawaiian group. Bull. U. S. Fish Commission, vol. 23, pt. 3, pp. 767-807.
- FITZBOGEN, J.
 1872. [Malden Island guano.] Ann. Landw. Wochenblatt, 1872, p. 310.
 Not seen; reference in Jour. Chem. Soc., 1872, vol. 25, p. 1112.
- FLACK, E. V.
 1916. Some factors influencing the solubility of phosphoric oxide in mixed fertilisers containing superphosphates. South African Jour. Sci., vol. 13, pp. 201-208.
- FLASCHENTRÄGER, B., AND P. B. MÜLLER
 1938. Zur Biologie der Oxalsäure. II. Versuche über oxalogene Verbindungen im Harn. Hoppe-Seyler's Zeitschr. Physiol. Chem., vol. 251, pp. 61-69.
- FLEISCHER, M.
 1944. Discussion. Amer. Min., vol. 29, p. 326.
- FORBES, DAVID
 1870. On the Aymara Indians of Bolivia and Peru. Jour. Ethnol. Soc. London, new ser., vol. 2, pp. 193-305.
- FORBES, H. O.
 1913. The Peruvian guano islands. Ibis, ser. 10, vol. 1, pp. 709-712.
 This is really an editorial note and is attributed to Sclater, the editor of the Ibis.
 1914a. Puntos principales del informe presentado al supremo Gobierno por el ornitólogo H. D. Forbes. 5ª Memoria. Lima, Compañía Administradora del Guano, pp. 57-105.
 1914b. Notes on Molina's pelican (*Pelecanus thagus*). Ibis, ser. 10, vol. 2, pp. 403-420.
 1914c. The Peruvian guano deposits. Amer. Fert., vol. 40, pp. 44-45.
- FOURCROY, ANTOINE FRANCOIS DE, AND LOUIS NICOLAS VAUQUELIN
 1806. Mémoire sur le guano, ou sur l'engrais naturel des îlots de la Mer du Sud, près des côtes du Pérou. Mem. Inst. Sci., Lettres et Arts, Sci., Math. et Phys., vol. 6, pp. 369-385.
- FRAAS, O.
 1872. Ausgrabung im Hohlenfels bei Schelllingen. Jahresh. Ver. Vaterländische Naturk. Württemberg, vol. 28, pp. 21-36.
- FRANKEL, J. J.
 1943. The constitution of the Langebaan phosphate rock. South African Jour. Sci., vol. 39, pp. 102-108.
- FRAPS, G. S.
 1906. Commercial fertilizers in 1905-1906. Texas Agr. Exp. Sta. Bull., no. 85, pp. 1-20.
- FRASER, C. MCLEAN
 1943. General account of the scientific work of the Velero III in the eastern Pacific, 1931-1941. Part II. Geographical and biological associations. Allan Hancock Pacific Expeditions, vol. 1, pp. 49-258.
- FREZIER, A. F.
 1716. Relation du voyage de la Mer du Sud aux côtes du Chili et du Pérou, fait pendant 1712, 1713, et 1714. Paris, J. G. Nyon, 298 pp., maps.
- THE FRIEND
 1870, 1871, 1873, 1874. A monthly journal, devoted to temperance, seamen, marine and general intelligence. Honolulu, Samuel C. Damon, editor.
 Reports (under various titles) on ships loading at central Pacific guano islands, May, 1870, February, 1871, February, April, 1873, February, 1874.
- FRODL, FRIEDRICH
 1923. Die Höhlen des mährischen Karstes als Lagerstätten von Düngephosphaten. Brno, Im Verlage des Verfassers (Druck der Polygrafia), 37 pp.
- FROES ABREU, S.
 1939. Observações sobre a Guiana maranhense. Rev. Brasileira de Geogr., Rio de Janeiro, Ano I, pp. 26-54.
- FRONDEL, CLIFFORD
 1941. Whitlockite: a new calcium phosphate, $\text{Ca}_3(\text{PO}_4)_2$. Amer. Min., vol. 26, pp. 145-152.
 1943. Mineralogy of the calcium phosphates in

- insular phosphate rock. *Ibid.*, vol. 28, pp. 215-232.
- FRONDEL, CLIFFORD, AND E. PRIEN
1942. Carbonate-apatite and hydroxyl-apatite in urinary calculi. *Science*, new ser., vol. 95, p. 431.
- FRUWIRTH, C.
1883. Ueber Höhlen. *Zeitschr. Deutschen u. Oesterreichischen Alpenver.*, vol. 14, pp. 1-37.
- FRYER, J. C. F.
1910. Bird and Dennis Island, Seychelles. Reports of the Percy Sladen Trust Expedition to the Indian Ocean in 1905. Vol. 3. *Trans. Linnean Soc. London*, ser. 2 (zool.), vol. 14, pp. 15-20.
1911. The structure and formation of Aldabra and neighbouring islands, with notes on their flora and fauna. Reports of the Percy Sladen Trust Expedition to the Indian Ocean in 1905. Vol. 3. *Ibid.*, ser. 2 (zool.), vol. 14, pp. 397-442.
- FUNKHOUSER, W. D.
1925. Wild life in Kentucky. *Kentucky Geol. Surv.*, ser. 6, vol. 16, 385 pp.
- GADOW, H., AND J. S. GARDINER
1907. Aves, with some notes on the distribution of the land-birds of the Seychelles. Reports of the Percy Sladen Trust Expedition to the Indian Ocean in 1905. Vol. 1. *Trans. Linnean Soc. London*, ser. 2 (zool.), vol. 12, pp. 103-110.
- GALE, H. S.
1912. Nitrate deposits. *Bull. U. S. Geol. Surv.*, no. 523, 36 pp.
- GALTSOFF, P. S.
1933. Pearl and Hermes Reef, Hawaii; hydrographical and biological observations. *Bull. Bernice P. Bishop Mus.*, no. 107, 49 pp.
- GAMARRA DULANTO, LUIS
1941. Relación entre la cantidad de alimento ingerido por las aves guaneras, y el guano aprovechable que producen. *Bol. Compañía Administradora Guano, Lima*, vol. 17, pp. 103-114.
1942. Informe sobre las investigaciones de pérdida de nitrógeno en las guanos. *Ibid.*, vol. 18, pp. 283-298.
- GARCILASO DE LA VEGA, YNCA
1609. Primera parte de los comentarios reales, que tratan del origen de los Yncas, reyes que fueron del Perú, de su idolatría, leyes, y gobierno en paz y en guerra, etc. Lisbon, Pedro Crasbeeck.
- GARDINER, J. STANLEY
1931. Coral reefs and atolls. London, Macmillan and Co., Ltd., 181 pp.
- GARDINER, J. STANLEY, AND C. FORSTER COOPER
1907. Description of the expedition. Reports of the Percy Sladen Trust Expedition to the Indian Ocean in 1905. Vol. 1. *Trans. Linnean Soc. London*, ser. 2 (zool.), vol. 12, pt. 1, pp. 1-56; pt. 2, pp. 111-175.
- GAUSE, G. F.
1934. The struggle for existence. Baltimore, Williams and Wilkins, 163 pp.
1935. Vérifications expérimentales de la théorie mathématique de la lutte pour la vie. Paris, 277 pp.
- GAUSE, G. F., AND A. A. WITT
1935. Behavior of mixed populations and the problem of natural selection. *Amer. Nat.*, vol. 69, pp. 596-609.
- GAUSSOIN, E.
1866. Memoir on the island of Navassa (West Indies). Baltimore, J. B. Rose, for Navassa Phosphate Co. of New York, 32 pp.
- GAUTIER, ARMAND
1893. Sur quelques phosphates minéraux nouveaux ou très rares et sur la genèse des phosphates naturels. *Bull. Soc. Chem. Française*, ser. 3, vol. 9, pp. 885-907.
1894. Sur un gisement de phosphates de chaux et d'alumine. *Ann. des Mines, Mém.*, ser. 9, vol. 5, pp. 1-53.
1914. Sur les minervites. *Compt. Rendus Acad. Sci., Paris*, vol. 158, pp. 912-920.
- GILBERT, H.
1884. Sydney Island. *Biedermann's Zentralbl.*, 1884, p. 785.
From *Magdeburgische Zeitung*, no. 121, 1884. *Abstract in Jour. Chem. Soc.*, vol. 48, p. 429.
1896. *Chem. Zeitg.*
An apparently incorrect reference in *Elschner*, 1913, p. 91.
- GILCHRIST, J. D. F.
1914a. An enquiry into the fluctuations in fish supply on the South African coast. Union of South Africa, Province of Cape of Good Hope, *Marine Biol. Rept.*, no. 2, pp. 8-35.
1914b. The snoek and allied fishes in South Africa. *Ibid.*, no. 2, pp. 116-127.
- GILE, P. L., AND J. O. CARRERO
1918. The bat guanos of Porto Rico and their fertilizing value. *Bull. Porto Rico Agr. Exp. Sta.*, no. 25, 66 pp.
- GILL, E. L.
1936. A first guide to South African birds. Cape Town, M. Miller, Ltd., 223 pp.
- GIRARDIN, J., AND BIDARD
1844. Note sur le guano ou huano, engrais des

îles de la Mer du Sud. Ann. Chem. Phys., ser. 3, vol. 10, pp. 113-115.

GIUA, M.

1919. Osservazioni sul guano della Sardegna. Gazz. Chim. Italiana, vol. 49, pp. 246-249.

GIUNTI, MICHELE

- 1881a. Su un guano di pipistrelli. Napoli, Tipogr. Acad. Reale Sci.

Not seen; reference in Paris, 1899. Perhaps reprinted from Ann. R. Scuola Sup. Agr. Portici.

- 1881b. Ricerche sulla diffusione del rame nel regno animale. Napoli, Tipogr. Acad. Reale Sci., 16 pp.

Evidently separately paged reprint from Ann. R. Scuola Agr. Portici, vol. 2.

GOESSMAN, C. A.

1885. Penguin Island guano, Cuba guano and bat guano. Second Ann. Rept. State Agr. Exp. Sta., Amherst, Massachusetts, 1884, pp. 134-135.

1892. Guano phosphates. Ninth Ann. Rept. State Agr. Exp. Sta., Amherst, Massachusetts, 1891, p. 307.

GÖTZINGER, G.

1919. Die Phosphathöhle von Csoklovina in Siebenbürgen. Mitt. Geogr. Gesellsch. in Wien, vol. 62, pp. 302-333.

1928. Die Phosphatvorräte in Österreich. Spelaol. Jahrb., vol. 7-9, pp. 98-104.

1931. Die Drachenhöhlenfluss-system und dessen Alter. In Abel, O., and G. Kyrle, Die Drachenhöhle bei Mixnitz. Vienna, (Verlag) Österr. Staatsdruckerei, Spelaol. Monogr., vols. 7, 8, pp. 109-132.

GOLDSCHMIDT, VIKTOR M.

1938. Geochemische Verteilungsgesetze der Elemente. IX. Die Mengenverhältnisse der Elemente und der Atom-Arten. Skr. Norske Videnskaps-Akad. Oslo, I, Math. Nat. Kl., 1937, no. 4, 148 pp.

GONZALEZ DE LA ROSA, M.

1908. Estudio de las antiqüedades peruanas halladas bajo el huano. Rev. Hist., Lima, vol. 3, pp. 39-45.

Goss, N. S.

1888. New and rare birds found breeding on the San Pedro Martir Isle. Auk, vol. 5, pp. 240-244.

GOULD, JOHN

1865. Handbook to the birds of Australia. London, published by the author, 2 vols.

GRAHAM, H. W.

1941. Plankton production in relation to character of water in the open Pacific. Jour. Marine Res., vol. 4, pp. 189-197.

GREAT BRITAIN, PARLIAMENTARY SESSIONAL PAPERS

1852. Return to an address of the Honourable The House of Commons, dated May 14, 1852; for a copy of correspondence between the merchants of Liverpool and the Foreign Office, respecting the newly-discovered guano islands of Lobos Afuera and Lobos de Tierra. Vol. 54, Accounts and Papers (27).

No. 32. Enclosure. M. de Rivero to the Earl of Malmesbury, London, 4 May 1852. (See Rivero, 1852.)

1854. Return to an address of the Honourable The House of Commons, dated February 14, 1854; for copies or extracts of any correspondence which the government have had with the Peruvian government on the subject of the importation of guano. Vol. 72, Accounts and Papers (34).

No. 18. The Secretary to the Admiralty to Mr. Addington:

Enclosure no. 2. W. H. McIntosh to Rear Admiral Moresby, "Pollard" at sea, August 29, 1853.

Enclosure no. 3. A statement of the quantities of guano exported from the Chincha Isles during the years 1850-1851.

Enclosure no. 4. American vessels sailed from and loading at the Chincha Isles from July 15 to Sept. 1853 and guano taken away.

- 1854-1855. Guano. Return to an address of the Honourable The House of Commons, dated 25 May, 1855; for a copy of any consular despatches communicated to the Board of Trade since the 1st day of January, respecting additional sources of supply of guano. Vol. 50, Accounts and Papers (21).

No. 1. From Consul [Charles E.] Kortright to the Earl of Clarendon, Carthagen, 10 December 1854.

No. 2. From Consul [Walter] Cope to the Earl of Clarendon, Quito, 16 December 1854.

No. 5. From Consul-General [Wm.] Miller to the Earl of Clarendon, Wahoo, 2 March 1855.

1857. Guano. Return to an address of the Honourable The House of Commons, dated 18 May 1857; for copies of the reports which have been received from naval officers on foreign station, including the coast of Africa in consequence of instructions sent out in 1844, 1852

and 1853, directing them to take every opportunity of ascertaining where any large supplies of guano existed or were likely to be discovered. Vol. 38, Accounts and Papers (14).

H. Merivale Esq. to Capt. Hamilton, 26 May, 1851.

No. 13. Capt. J. Everard Home to Secretary of the Admiralty, "Calliope," Hobart Town, 26 April, 1852.

No. 35. Extract of a letter from Rear Admiral Moresby to the Secretary of the Admiralty, Callao, 25 June, 1853.

No. 115. Rear Admiral [Arthur] Fanshawe, "Vestal," at Halifax, 25 August, 1854. (Enclosure from Commander de Horsey to Commander Henderson.)

Extract from a letter of Capt. Stephen Freemantle addressed to the Earl of Clarendon, "Juno," 10 October 1854.

No. 127. Rear Admiral Fanshawe to the Secretary of the Admiralty, "Boscawen" at Bermuda, 10 May, 1856. (Enclosure from Capt. Henry Coryton, "Hermes," Port Royal, 16 April, 1856.)

No. 11. Enclosure. Extract of a letter from Capt. Paynter, H.M.S. Brilliant, 28 February 1857.

Further material is to be found in Return to an Address of the Honourable The House of Commons, dated July 24, 1856; for copies or extracts of correspondence with the Colonial Office, respecting a grant made by the Crown to raise and take away guano from the islands of Jiblea, etc. Vol. 38, Accounts and Papers (14).

No. 82. (This is a group of 33 letters, including an extract of a dispatch from C. Freemantle to the Earl of Clarendon, "Juno," 18 July 1854.)

No. 308. In continuation of no. 82. (This is a group of 39 letters.)

- 1874a. Foreign Office. Commercial no. 10. Reports furnished to the Board of Admiralty and communicated to the Foreign Office relative to guano deposits in Peru. Presented to both Houses by command of Her Majesty. London, vol. 68, 11 pp.

Correspondence and reports by Rear Admiral A. A. Cochrane and Capt. C. S. Stanley.

- 1874b. Foreign Office. Commercial no. 11. Further reports furnished to the Board of Admiralty and communicated to the Foreign Office relative to guano de-

posits in Peru. Presented to both Houses by command of Her Majesty. London, vol. 68, pp. 1-4.

Letter of Rear Admiral A. A. Cochrane transmitting Cookson, 1874a.

- 1874c. Foreign Office. Commercial no. 17. Report upon the guano deposits on the islands of Lobos de Tierra, Lobos de Afuera, Macabi and Guafape. Presented to both Houses by command of Her Majesty. London, vol. 68, 3 pp.

A. A. Cochrane transmitting Cookson, 1874b.

1876. Foreign Office. Commercial no. 1. Report upon the guano deposits on the islands of Lobos de Tierra, Lobos de Afuera, Macabi and Guafape. [In continuation of commercial no. 17, 1874c.] London, vol. 76, 3 pp.

Rear Admiral A. A. Cochrane transmitting Cookson, 1876.

- 1844-1891. Accounts and Papers. Trade and Navigation.

Consult years concerned, under General Imports and General Exports, for statistics on tons of guano exported from and imported to Great Britain.

GREENSTREET, V. R.

1926. Malayan guano deposits. Malayan Agr. Jour., vol. 14, pp. 106-115.

GRINNELL, JOSEPH, AND FRANK SLATER DAGGETT

1903. An ornithological visit to Los Coronados Islands, Lower California. Auk, vol. 20, p. 27.

GRUNER, I. W., AND D. MCCONNELL

1937. The problem of the carbonate-apatites. The structure of francolite. Zeitschr. Krist., vol. 97, pp. 208-215.

GRUSS, L.

1940. The "Mission" to Ecuador of Judah P. Benjamin. Louisiana Hist. Quart., vol. 23, pp. 162-169.

GRUTTERINK, J. A.

1928. Dutch Antilles. Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates, vol. 2, pp. 663-666.

GUILD, F. N.

1910. The mineralogy of Arizona. Easton, Pennsylvania, Chemical Publishing Co., 103 pp.

GUILLAIS

1856. Documents sur l'histoire, la géographie et le commerce de l'Afrique orientale. Paris, A. Bertrand, vol. 1, pt. 2.

Not seen, reference on p. 380 in Meise, 1938, for Abd-el Kuri, Kal Farun.

- GULINO, GUISEPPE, AND GIAMBATTISTA DAL PIAZ
1939. I Chirrotteri Italiani. Boll. Mus. Zool.

- Anat. Comp. Torino, vol. 47, pp. 61-103.
- GUNTHER, E. R.
1936. A report on oceanographical investigations in the Peru coastal current. Great Britain Colonial Office Discovery Repts., vol. 13, pp. 107-276.
- GUTHRIE, MARY J.
1933. Notes on the seasonal movements and habits of some cave bats. Jour. Mammal., vol. 14, pp. 1-19.
- HABEL, A.
1871. The mode of occurrence of the Whuano (guano) on the Chincha Islands. Proc. Lyceum Nat. Hist., ser. 1, pp. 225-229. Cf. also Zeitschr. Gesellsch. Naturwiss., vol. 4, pp. 32-38, and Wiener Anz., vol. 12, p. 141, not seen but probably identical material.
- HAGUE, J. D.
1862. On phosphatic guano islands of the Pacific Ocean. Amer. Jour. Sci., ser. 2, vol. 34, pp. 224-243.
- HAINES, S. B.
1857. The Kooria Moorla Islands. Nautical Mag., vol. 26, pp. 385-389.
- HAMBRUCH, P.
1914. Nauru. In Thilenius, G., Ergebnisse der Südsee-Expedition 1908-1910. II. Ethnographie: B. Mikronesien, Band 1. Hamburg, L. Friederichsen u. Co., pt. 1.
- HANZAWA, S.
1935. Topography and geology of the Riukiu Islands. Sci. Repts. Tōhoku Imp. Univ. Sendai, Japan, ser. 2 (geol.), vol. 17, pp. 1-61.
1938. Studies on the Foraminifera fauna found in the bore cores from the deep well in Kita-Daito-Zima (North Borodino Island). Proc. Imp. Acad. Tokyo, vol. 14, pp. 384-390.
- HARF, R. F.
1904. Report of the chemist. New Mexico Agr. Exp. Sta., 15th Ann. Rept., pp. 36-40.
- HARRINGTON, H. H.
1899. Fertilizers and fertilizer analyses. Bull. Texas Agr. Exp. Sta., no. 51, pp. 22-37.
- HARRINGTON, MARK R.
1933. Gypsum Cave, Nevada. Southwest Mus. Papers, no. 8, 197 pp.
- HARRIS, J. H.
1870. [Note on exhibition of carved wooden club found beneath deposit of guano in island of South Guañape off Trujillo on the coast of Peru.] Proc. Ethnog. Soc., Nov. 8, 1870, p. xxxix, in Jour. Roy. Anthropol. Inst., vol. 1, 1872.
- HARTT, C. F.
1870. Thayer expedition. Scientific results of a journey in Brazil. . . . Geology and physical geography. Boston, xxiii+620 pp.
- HAUGHTON, S. H.
1932. The late Tertiary and recent deposits of the west coast of South Africa. Trans. Geol. Soc. South Africa, for 1931, vol. 34, pp. 19-57.
1933. On the phosphate deposits near Langebaan Road, Cape Province. *Ibid.*, for 1932, vol. 35, pp. 119-124.
- HAYES, A. A.
1855. Report on a specimen of fossilized egg from the guano islands off the coast of Peru. Proc. Boston Soc. Nat. Hist., vol. 5, p. 165.
- HECTOR, J., AND W. SKEY
1865. Reports of the jurors, New Zealand exhibition. Dunedin, 1866, p. 423.
- HEIDEN, E.
1887. Lehrbuch der Düngerlehre. [Second edition.] Hannover, Philipp Cohen, vol. 2.
- HEILPRIN, ANGELO
1906. Impressions of a naturalist in British Guiana. Bull. Amer. Geogr. Soc., vol. 38, pp. 539-553.
- HELLER, FLORIAN
1936. Eine oberpliocäne Wirbeltierfauna aus Rheinhessen. Neues Jahrb. Min. Geol. u. Paläont., suppl. vol. 76B, pp. 99-160.
- HENDRICKS, STERLING B., AND W. L. HILL
1942. The inorganic constitution of bone. Science, vol. 96, no. 2489, pp. 255-257.
- HENDRICKS, STERLING B., W. L. HILL, K. D. JACOB, AND M. E. JEFFERSON
1931. Structural characteristics of apatite-like substances and composition of phosphate rock and bone as determined from microscopical and X-ray diffraction examinations. Indust. Engin. Chem., vol. 23, pp. 1413-1418.
- HENDRICKS, STERLING B., M. E. JEFFERSON, AND V. M. MOSELY
1932. The crystal structures of some natural and synthetic apatite-like substances. Zeitschr. Krist., vol. 81, pp. 352-369.
- HENTSCHEL, E.
1928. Die Grundzüge der Planktonverteilung im Südatlantischen Ozean. Internatl. Rev. ges. Hydrobiol. Hydrogr., vol. 21, pp. 1-16.
1933. Allgemeine Biologie des Südatlantischen Ozeans. In Defant, Albert, Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition . . . "Meteor" 1925-1927. Band XI. Berlin and Leip-

- zig, Walter de Gruyter u. Co., pt. 1, Das Pelagial der obersten Wasserschicht, pp. 1-168 (Das Pteropleuston, pp. 116-122).
1936. Allgemeine Biologie des Südatlantischen Ozeans. In Defant, Albert, *op. cit.*, Band XI. Berlin and Leipzig, Walter de Gruyter u. Co., pt. 2, Das Pelagial der unteren Wasserschichten, pp. 169-344.
- HENTSCHEL, E., AND H. WATTENBERG
1930. Plankton und Phosphat in der Oberflächenschicht des Südatlantischen Ozeans. Ann. Hydrogr., vol. 58, pp. 273-277.
- HERAPATH, T. J.
1849. On some newly discovered substances from the African guano deposits. Quart. Jour. Chem. Soc., vol. 2, pp. 70-74.
- HERMS, W. B.
1926. *Diocalandra taitensis* (Guerin) and other coconut pests of Fanning and Washington Islands. Philippine Jour. Sci., vol. 30, pp. 243-274.
- HESS, WILLIAM H.
1900. The origin of nitrates in cavern earths. Jour. Geol., vol. 8, pp. 129-134.
- HEUGLIN, TH. VON
1873. Ornithologie Nordost-Afrika's, der Nilquellen- und Küsten-Gebiete des Rothen Meeres und des nördlichen Somal-Landes. Cassel, (Verlag) T. Fischer, vol. 2, pp. 853-1512.
- HEWITT, J. H. C.
1937. The government guano islands (Annual Report by the Superintendent). Farming in South Africa, Dec., 1937, pp. 591-592.
1938. The government guano islands (Annual Report by the Superintendent). *Ibid.*, Dec., 1938, pp. 589-590.
- HICKSON, SYDNEY J.
1889. A naturalist in North Celebes. London, John Murray, 392 pp.
- HIGGINS, J., AND C. BICKELL
1857. On Columbian guano, its composition and character. Amer. Jour. Sci., ser. 2, vol. 23, pp. 121-123.
- HILL, W. L., AND STERLING B. HENDRICKS
1936. Composition and properties of superphosphate. Indust. Engin. Chem., vol. 28, pp. 440-447.
- HITCHCOCK, C. H.
1891. The Redonda phosphate. Bull. Geol. Soc. Amer., vol. 2, pp. 6-9.
- HOBBS, WILLIAM HERBERT
1945. The fortress islands of the Pacific. Ann Arbor, Michigan, J. W. Edwards, 186 pp.
- HOFFMAN, G. C.
1890. Annotated list of the minerals occurring in Canada. Geol. and Nat. Hist. Surv. Canada, 1890.
- HOLDEN, E. S., AND E. F. QUALTROUGH
1884. Report of the Eclipse expedition to Caroline Island, May 1883. IV 2. Description of the island. Mem. Natl. Acad. Sci., vol. 2, pp. 22-26.
- HOLZSCHNEIDER, H.
1937. Die Vogelberge, Guano- und Inselphosphatlagerstätten der Erde. Düsseldorf, Inaug.-Diss. Bonn, 104 pp.
- HOPPE-SEYLER, F.
1863. Lithofellinsäure und die Guanogallensäure. Chem. Zentralbl., new ser., vol. 8, no. 48, pp. 753-756.
1871. Physiologico-chemical notices. 2. Guanine in the urine of the heron (*Ardea cinerea*). Jour. Chem. Soc., vol. 24, pp. 848-849.
Abstract from Med. Chem. Untersuch., 1871, pp. 582-587.
- HOWELL, ARTHUR H.
1921. A biological survey of Alabama. I. Physiography and life zones. II. The mammals. North American Fauna, no. 45, U. S. Dept. Agr., Bur. Biol. Surv., 88 pp.
- HOWITT, A. M.
1928. Phosphate in Victoria. The Mansfield deposit. Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates, vol. 2, pp. 833-898.
- HUBBARD, B.
1923. The geology of the Lares District, Porto Rico. New York Acad. Sci., Scientific Survey of Porto Rico and the Virgin Islands, vol. 2, pt. 1, pp. 1-115.
- HÜBENER, TH.
1898. Die Inseln Mona und Monito. Globus, vol. 74, pp. 368-372.
- HUGHES, G.
1885. On some West Indian phosphates. Quart. Jour. Geol. Soc. London, vol. 41, pp. 80-81.
- HUGHES, T. MCKENNY
1874. Exploration of Cave Ha, near Giggleswick, Settle, Yorkshire. Jour. Anthropol. Inst., vol. 3, pp. 382-387.
- HUMBOLDT, A. VON
1806. Chemische Untersuchung des Guano aus den Inseln der Peruanischen Küste. Klaproth's Beiträge zur Chemischen Kenntnis der Mineralkörper, vol. 4, pp. 299-313.
Not seen; reference in W[ohler, F.], 1841; cf. also Fourcroy and Vauquelin, 1806.

1817. Voyages aux régions équinoxiales du Nouveau Continent. Paris, vol. 3, 381 pp.
Steatornis on pp. 149-175.
- HUNT, H. A.
1914. Meteorology of Australia (Commonwealth Bureau of Meteorology). 3. Results of rainfall observations made in Queensland. Melbourne, 285 pp.
- HUNT, T. S.
1855. Mineralogical notes. Amer. Jour. Sci., ser. 2, vol. 19, pp. 428-429.
- HUTCHINSON, G. E.
1947. A note on the theory of competition between two social species. Ecology, vol. 28, pp. 319-321.
- HUTCHINSON, R. C.
1941. Phosphate deposits in New Guinea. New Guinea Agr. Gaz., vol. 7, pp. 239-245.
- HUTCHINSON, T. J.
1873. Two years in Peru. London, S. Low, Marston, Low and Searle, vol. 1, 343 pp.; vol. 2, 334 pp.
- INGLE, HERBERT
1913. A manual of agricultural chemistry. Third edition. London, Scott Greenwood and Son, v+397 pp.
Guano, pp. 120-124.
- INGRAMS, W. H.
19-?. History and description of Latham Island. Undated printed sheet in Zanzibar Museum, which may have appeared as a supplement to the Zanzibar Government Gazette between 1924-1930.
Not seen; reference in Moreau, 1940.
- D'INVILLIERS, E. V.
1891. The phosphate deposits of the island of Navassa. Bull. Geol. Soc. Amer., vol. 2, pp. 75-84.
- IRVING, EARL M., AND JUAN S. TEVES
1947. Guano caves of Pupug, Municipality of Mabini, Bohol, P.I. Philippine Geol., vol. 1, pt. 4, pp. 1-8.
Not seen; reference in Chem. Abstr., 1949, vol. 43, p. 71.
- JACK, R. LOCKHART
1919. Phosphate deposits of South Australia. Bull. Dept. Mines, Geol. Surv. South Australia, no. 7, 136 pp.
- JACKSON, C. H.
1897. Report on the Government Guano Islands for the year 1896. Cape Town, G. 67, pp. 1-5.
1900. Report of the Superintendent of the Government Guano Islands for the year 1899. G. 17, pp. 1-7.
1901. Report of the Superintendent of the Government Guano Islands for the year 1900. G. 29, pp. 1-5.
1902. Report of the Superintendent of the Government Guano Islands for the year 1901. G. 33, pp. 1-6.
1903. Report of the Superintendent of the Government Guano Islands for the year 1902. G. 17, pp. 1-4.
1904. Report of the Superintendent of the Government Guano Islands for the year 1903. G. 50, pp. 1-4.
1906. Report of the Superintendent of the Government Guano Islands for the half year ended 31st Dec. 1904 and for the year 1905. G. 36, pp. 1-7.
1907. Report of the Superintendent of the Government Guano Islands for the year 1906. G. 33, pp. 1-4.
1929. A valuable asset to the farmer. Farming in South Africa, 1929, p. 444.
1930. A valuable asset to the farmer. *Ibid.*, 1930, p. 428.
1931. The government guano islands. *Ibid.*, 1931, p. 359.
1933. Report on the government guano islands. *Ibid.*, 1933, p. 518.
1934. Report on the government guano islands. *Ibid.*, 1934, p. 581.
1935. The government guano islands. *Ibid.*, 1935, p. 596.
- JACOB, K. D., W. L. HILL, H. L. MARSHALL, AND D. S. REYNOLDS
1933. The composition and distribution of phosphate rock with special reference to the United States. Tech. Bull. U. S. Dept. Agr., no. 364, 89 pp.
- JANISCH, H. R.
1885. Extracts from St. Helena records from 1673-1835. Jamestown, St. Helena.
- JEANNEL, RENÉ
1926. Faune cavernicole de la France avec étude des conditions d'existence dans le domaine souterrain. Paris, P. Lechevalier, 334 pp.
- JEANNEL, RENÉ, AND E. G. RACOVITZA
1907. Biospéologica II. Énumération des grottes visitées. 1^{re} ser. Arch. Zool. Exp. Gén., ser. 4, vol. 6, pp. 489-536.
1908. Biospéologica VI. Énumération des grottes visitées. 2^{me} ser. *Ibid.*, ser. 4, vol. 8, pp. 327-414.
1910. Biospéologica XVI. Énumération des grottes visitées. 3^{me} ser. *Ibid.*, ser. 5, vol. 5, pp. 67-185.
1912. Biospéologica XXIV. Énumération des grottes visitées. 4^{me} ser. *Ibid.*, ser. 5, vol. 9, pp. 501-667.
1914. Biospéologica XXXIII. Énumération

- des grottes visitées. 5^{me} ser. *Ibid.*, vol. 53, pp. 325-558.
1918. Biospéologica XXXIX. Enumération des grottes visitées. 6^{me} ser. *Ibid.*, vol. 57, pp. 203-470.
1929. Biospéologica LIV. Enumération des grottes visitées. 7^{me} ser. *Ibid.*, vol. 68, pp. 293-608.
- JIMÉNEZ DE LA ESPADA, M., (EDITOR)
1881. Relaciones geográficas de Indias. Publicadas el Ministerio de fomento. Peru . . . Madrid, Tip. de Manuel G. Hernandez, vol. 1, appendix 2, being an extract from Francisco López de Caravantes: Noticia general del Perú y tierra Firme, MS 1630 and in footnote thereto on p. cxxxviii: extract from Pedro de Avendaño: Apuntamientos para el buen gobierno del Perú, MS 1564 or 1565.
- JOHNSON, G. R.
1930. Peru from the air (with text and notes by R. R. Platt). Amer. Geogr. Soc., special publ. no. 12, 159 pp.
- JOHNSTON, I. M.
1931. The vascular flora of the guano islands of Peru. Contrib. Gray Herbarium, Harvard Univ., vol. 95, no. 2, pp. 26-35.
- JOLIBOIS, PIERRE, AND CLAUDE HÉBERT
1946. Sur la composition chimique des phosphates de calcium naturels. Compt. Rendus Acad. Sci., Paris, vol. 222, pp. 569-572.
- JONES, MAUDE
1946. Letter to the editors. New Yorker Mag., Feb. 2, p. 62.
- JUAN, GEORGE (JORGE JUAN Y SANTACILIA), AND ANTONIO DE ULLOA
1806. A voyage to South America. Fourth edition. London, Printed for J. Stockdale, vol. 2, 419 pp.,
Guano, pp. 99-100. Apparently originally published in Spanish in 1748.
- JULIEN, A. A.
1867. On the geology of the key of Sombrero, W. I. Ann. Lyceum Nat. Hist., New York, for 1866, vol. 8, pp. 251-278.
- KAISER, E.
1930. Das Fischsterben in der Walfischbucht. Palaeobiologica, vol. 3, pp. 14-20.
- KANAMORI, S.
1907. On bat guano from Marianne Islands. Bull. College Agr., Tokyo Imp. Univ., Japan, vol. 7, pp. 461-464.
- KARMRODT, C.
1861. Zeitschr. Landw. Ver. von Rheinpreussen, p. 401.
Not seen; reference in Heiden, 1887.
1873. Zeitschr. Landw. Ver. von Rheinpreussen, p. 38.
Not seen; reference in Jahresb. Agr. Chem., 1877, 16-17 Jahrg., vol. 3, p. 23.
- KARWOWSKY, A.
1881. Analyse von Fledermausexkrementen. Z. rusk. Chim. obsc., vol. 13, pp. 387-388.
Not seen; abstract in Chem. Zentralbl., 1882, vol. 53, p. 25.
- KAZAKOV, A. V.
1937. Chemical nature of the phosphate substance of phosphorites and their genesis. I. The system $\text{CaO-P}_2\text{O}_5\text{-H}_2\text{O}$ in the field of low concentration. Trans. Sci. Inst. Fertilizers Insectofungicides, U. S. S. R., no. 139, pp. 3-73.
- KEYLE, G. S.
1861. Fanning's Island—an incident. Friend, vol. 10, p. 35.
- KIDSON, E.
1930. Meteorological observations for 1928. New Zealand, Dept. Sci. and Indust. Res., Wellington, New Zealand, W. A. G. Skinner, Govt. Printer, 28 pp.
- KILLIP, E. P.
1939. Flowering plants collected on the Presidential cruise of 1938. Smithsonian Misc. Coll., vol. 98, no. 8, 4 pp.
- KINAHAN, J. R.
1856. Some account of the guano deposits and inhabitants of the Chincha Islands, Peru. Jour. Roy. Dublin Soc., vol. 1, pp. 89-100.
- KINNEAR, N. B.
1934. Zoological notes from the voyage of Peter Mundy, 1655-1656. (a) Birds. Proc. Linnean Soc. London, Session 1934-1935, pt. 2, pp. 32-33.
- KINNERSLEY, H. W., R. A. PETERS, AND B. T. SQUIRES
1925. Animal quinoidine. Biochem. Jour., vol. 19, pp. 404-413.
- KIRBY, H., JR.
1925. The birds of Fanning Island, central Pacific Ocean. Condor, vol. 27, pp. 185-196.
- KITSON, SIR ALBERT
1931. Geological notes on St. Helena, by various writers, with remarks on the economic geology of that island, and geological map. London, His Majesty's Stationery Office, 22 pp.
- KLAPROTH, MARTIN H.
1806. Chemische Untersuchung des Guano aus den Inseln der Peruanischen Küste. Beiträge zur Chemischen Kenntnis der Mineralkörper, vol. 4, pp. 299-313.

- Not seen; reference in W[ohler, F.], 1841.
- KLEMENT, R.
1936. Basische Phosphate zweiwertiger Metalle. I. Basische Magnesium Phosphate. *Zeitschr. anorg. Chem.*, vol. 228, pp. 232-240.
- KLEMENT, R., AND P. DIHN
1938. Über Kalk-Alkaliphosphate. Bemerkungen zu den gleichnamigen Arbeiten von H. H. Franck und Mitarbeitern. *Zeitschr. anorg. Chem.*, vol. 240, pp. 40-49.
- KLEMENT, R., AND F. ZUREDA
1940. Basische Phosphate zweiwertiger Metalle. V. Phosphate und Hydroxylapatit des Cadmiums. *Zeitschr. anorg. Chem.*, vol. 245, pp. 229-235.
- KLOOS, J. H.
1888. Untersuchungen ueber Gesteine und Mineralien aus West-Indien. *Samml. des geol. Reichs-Mus. in Leiden*, ser. 2, Beitr. geol. Niederländisch-West-Indien u. angrenzender Gebiete, vol. 1, no. 1, pp. 1-110.
- KNECHT, THEODORO
1940. Os minérios não metálicos do Estado de São Paulo. *Bol. Inst. Geogr. e Geol.*, no. 27, 291 pp.
- KÖNIG, (FRANZ) JOSEF
1898. Die Untersuchung landwirtschaftlicher ... Stoffe. Zweite, neubearbeitete Auflage. Berlin, Paul Parey, 824 pp.
1906. Die Untersuchung landwirtschaftlicher ... Stoffe. [Third edition.] Berlin, Paul Parey, 1083 pp.
1923. Die Untersuchung landwirtschaftlicher ... Stoffe. Fünfte, neubearbeitete Auflage. Berlin, Paul Parey, vol. 1. Not seen; reference in Popp and Marxen, 1931.
- KORMOS, THEODOR (TIVADAR)
1934. Neue Insektenfresser, Fledermäuse und Nager aus dem Oberpliozän der Villanyer Gegend. *Földtani Közlöny*, vol. 64, pp. 296-321.
- KORTLANDT, A.
1942. Levensloop, samenstelling en Structuur der Nederlandse aalscholver Bevolking. *Ardea*, vol. 31, pp. 175-280.
- KREBS, H. A., AND L. V. EGGLESTON
1939. Bacterial urea formation. *Enzymologia*, vol. 7, pp. 310-320.
- KRIGE, A. V.
1927. An examination of the Tertiary and Quaternary changes of sea-level in South Africa, with special stress on the evidence in favour of a recent worldwide sinking of ocean-level. *Ann. Univ. Stellenbosch*, vol. 5, sect. A, pt. 1.
- KROCKER, F.
1873. *Landw. Centralb. f. Deutschland*, p. 143.
Not seen; reference in *Jahresb. Agr. Chem.*, 1877, 16-17 Jahrg., vol. 3, p. 23.
- KRUEGER, J.
1944. Sterols from Peruvian guano. *Jour. Amer. Chem. Soc.*, vol. 66, p. 1795.
- KRULL, W.
1894. Estudio sobre dos guaneras i la descomposicion del guano. *Bol. Soc. Nac. Minería, Santiago, Chile*, vol. 11 (ser. 2, vol. 6), pp. 254-258, 306-314.
- KUBLER, GEORGE ALEXANDER
1948. Towards absolute time: guano archaeology. *Mem. Soc. Amer. Archaeol.*, suppl. to *Amer. Antiquity*, vol. 13, no. 4, pt. 2, pp. 29-50.
- KYRLE, G.
1931. Kulturreste. In Abel, O., and G. Kyrle, *Die Drachenhöhle bei Mixnitz*. Vienna, (Verlag) Österr. Staatsdruckerei, Spelaol. Monogr., vols. 7, 8, pp. 795-882.
- LACROIX, A.
1886. Sur un minéral probablement nouveau (dans le guano du Pérou). *Bull. Soc. Française Min.*, vol. 9, p. 51.
1888. Sur la bobierite. *Compt. Rendus Acad. Sci.*, Paris, vol. 106, pp. 631-633.
1905. Sur un gisement de redondite à la Martinique. *Bull. Soc. Française Min.*, vol. 28, pp. 13-16.
1906. Sur la transformation des roches volcaniques en phosphate d'alumine sous l'influence de produits d'origine physiologique. *Compt. Rendus Acad. Sci.*, Paris, vol. 143, pp. 661-664.
1910. Sur l'existence d'une variété de minervite à la Réunion. *Bull. Soc. Française Min.*, vol. 33, pp. 34-39.
1911. Les syénites néphéliniques de l'archipel de Los et leurs minéraux. *Nouv. Arch. Mus.*, Paris, ser. 5, vol. 3, pp. 1-132.
1912. Sur les minéraux du guano de la Réunion. *Bull. Soc. Française Min.*, vol. 35, pp. 114-119.
1918. Le gisement phosphate de l'île Juan de Nova. *Ibid.*, vol. 41, pp. 100-103.
1936. Le volcan actif de l'île de la Réunion et ses produits. Paris, Gauthier-Villars, 297 pp., pls.
- LADD, HARRY S., AND J. EDWARD HOFFMEISTER
1945. Geology of Lau, Fiji. *Bull. Bernice P. Bishop Mus.*, no. 181, 399 pp.

- LAMARMORA, ALBERTO FERRERO DE
1860. Itinéraire de l'île de Sardaigne. Turin, vol. 2, 603 pp.
Bat guano, p. 78.
- LAMBRECHT, KÁLMÁN
1933. Handbuch der Palaeornithologie. Berlin, Borntraeger, 1024 pp.
- LARROQUE, LUIS
1863. Informe sobre los depósitos de guano de Mejillones. Santiago, Chile, Imprenta nacional, 187 pp.
- LASNE, H.
1890. Identité de composition de quelques phosphates sédimentaires avec l'apatite. Compt. Rendus Acad. Sci., Paris, vol. 110, pp. 1376-1377.
- LAUDERMILK, J. D., AND PHILIP A. MUNTZ
1938. Plants in the dung of *Nothrotherium* from Rampart and Muav caves, Arizona. Contrib. to Palaeont. Studies on Cenozoic Vertebrates of Western North America, paper no. 8, pp. 271-281.
- LAURENT, P.
1937. Essai d'une clef dichotomique des chéiroptères de la Barbarie. Mammalia, vol. 1, pp. 133-159.
- LAVALLE Y GARCÍA, J. A. DE
1912. Cuánto cuesta producir una libra de algodón en la costa del Perú? II. La Riqueza Agrícola, vol. 1, pp. 621-625.
1917. Informe preliminar sobre la causa de la mortalidad anormal de las aves ocurrida en el mes de marzo del presente año. Mem. Compañía Administradora Guano, Lima, vol. 8, pp. 61-88.
1918. Estudio de los factores que influyen sobre la distribución de los nidos de las aves productoras de guano. *Ibid.*, vol. 9, pp. 205-213.
1920. Datos para el estudio de la relación entre las épocas de realización de las principales facies de la vida de las aves y las condiciones climáticas. *Ibid.*, vol. 11, pp. 77-168.
1924. Estudio de la emigración y mortalidad de las aves guaneras. Comp. Administradora Guano, Lima, Sección Técnica.
- LEDoux, A. R.
1890. The newly-discovered phosphate-beds of Florida. Trans. New York Acad. Sci., vol. 9, pp. 84-95.
- LEITMEIER, H., AND H. HELLWIG
1920. Versuche über die Entstehung von Tonerdephosphaten. Festschrift C. Doelter, Dresden and Leipzig, pp. 41-67, 2 figs.
Abstract in Min. Abstr., 1924, vol. 2, p. 380.
- LEONARDOS, OTHON HENRY
1945. Recursos do Brasil em fosfatos minerais. Mineração e Metalurgia, vol. 8, no. 46, pp. 263-268.
- LEWIS, A. D.
1938. Rainfall normals up to the end of 1935. Pretoria, Government Printer, 162 pp.
- LEWIS, HARRISON F.
1929. The natural history of the double-crested cormorant. Ithaca, New York, and Ru-mi-lou Books, Ottawa, Canada, (auspices of the Province of Quebec Society for the Protection of Birds), 92 pp.
- LIEBERT, F.
1909. The decomposition of uric acid by bacteria. K. Akad. Wetensch. Amsterdam, Proc. Sect. Sci., vol. 12, pt. 1, pp. 54-64.
- LIEBIG, JUSTUS VON
1860. Ueber Baker-, Jarvis- und Howland-Guano.
Reprinted or very fully abstracted from Zeitschr. Landw. Ver. in Baiern, Sept., 1860, with above title in Chem. Centralbl., 1861, new ser., vol. 6, pp. 264-269.
- LIESEGANG, C.
1940. Die Phosphatvorkommen der Südsee. Glückauf. Berg- und Huttenmännische Zeitg., vol. 76, no. 6, pp. 82-85.
- LINCOLN, R.
1939. Report of chemical division. Ann. Rept. Dept. Agr. Mauritius, 1938, pp. 51-57.
- LIPMAN, C. B., AND P. E. SHELLEY
1924. Studies on the origin and composition of the soil of Rose Islet. Papers Dept. Marine Biol. Carnegie Inst. Washington, vol. 19, pp. 201-208.
- LISTER, J. J.
1891. Notes on the birds of the Phoenix Islands, Pacific Ocean. Proc. Zool. Soc. London, pp. 289-300.
- LORAH, J. R., H. V. TARTAR, AND L. WOOD
1929. A basic phosphate of calcium and of strontium and the adsorption of calcium hydroxide by basic calcium phosphate and by tricalcium phosphate. Jour. Amer. Chem. Soc., vol. 51, pp. 1097-1106.
- LOWE, P. R.
1909. Notes on some birds collected during a cruise in the Caribbean Sea. Ibis, ser. 9, vol. 3, pp. 304-347.
1911. A naturalist on desert islands. London, Witherby and Co., 300 pp.
- LOWE, W. P.
1912. Description of Ichabo Island. Ibis, ser. 9, vol. 6, pp. 263-268.
Appendix to Bannerman, David, 1928.

- LULL, RICHARD SWANN
1929. A remarkable ground sloth. *Mem. Peabody Mus., Yale Univ.*, vol. 3, pt. 2, 21 pp., 9 pls.
- LYNGE, B.
1934. General results of recent Norwegian research work on arctic lichens. *Rhodor*, vol. 36, pp. 133-171.
- McCONNELL, D.
1938. A structural investigation of the isomorphism of the apatite group. *Amer. Min.*, vol. 23, pp. 1-19.
1941. Barrandita, mineral constitutivo de los depósitos de fosfato de la Isla Gran Roque, D. F., Venezuela. *Rev. Colegio Ing. Venezuela*, vol. 19, no. 140, pp. 115-119.
1943. Phosphatization at Malpelo Island, Colombia. *Bull. Geol. Soc. Amer.*, vol. 54, pp. 707-716.
1950. The petrography of rock phosphates. *Jour. Geol.*, vol. 58, pp. 16-23.
- McDONALD, W. F.
1938. Atlas of climatic charts of the oceans. U. S. Weather Bureau, no. 1247, U. S. Dept. Agr., 130 charts on 65 pp.
- MAC ENERY, J.
1869. In Pengelly, W., The literature of Kent's Cavern. Part II. Including the whole of the Rev. J. Mac Enery's manuscript. *Rept. and Trans. Devonshire Assoc. Adv. Sci. Litt.*, vol. 3, pp. 191-482.
- McFARLAN, A. C.
1943. Geology of Kentucky. Lexington, Kentucky, University of Kentucky, 531 pp.
- MACHATSCHKI, F.
1931. Beiträge zur Kenntnis der Ablagerungen. In Abel, O., and G. Kyrle, Die Drachenhöhle bei Mixnitz. Vienna, (Verlag) Österr. Staatsdruckerei, Spelaeol. Monogr., vols. 7, 8, pp. 225-245.
- MACIVOR, R. W. EMERSON
1887. On Australian bat guano and some minerals occurring therein. *Chem. News*, vol. 55, pp. 215-216.
1902a. On minerals occurring in Australian bat guano. *Ibid.*, vol. 85, pp. 181-182.
1902b. Further note on minerals occurring in Australian bat guano. *Ibid.*, vol. 85, p. 217.
- M'MURTRIE
1874. Bat excrement. *Amer. Chem.*, vol. 4, no. 45, p. 339.
- MAGNUS
1844. Ueber das Vorkommen von Xanthoxyd im Guano. *Ann. Chem. u. Pharm.*, vol. 51, pp. 395-397.
- MAGNUSSON, A. H.
1942. Lichens of Nihoa and Necker Islands. *Occas. Papers Bernice P. Bishop Mus.*, vol. 17, no. 2, pp. 25-41.
- MAITLAND, A. GIBB
1928. The phosphate resources of Western Australia. *Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates*, vol. 2, pp. 815-822.
- MALAGUTI, M.
1861. Observations sur quelques substances fertilisantes désignées sous le nom générique de Guano de Patagonie. *Compt. Rendus Acad. Sci., Paris*, vol. 53, pp. 436-442.
- MANGON, HERVÉ
1857. Note sur l'engrais produit par les chauves-souris. *Bull. Soc. d'Encouragement Indust. Natl.*, vol. 56, pp. 694-695.
- MANN, ALEXANDER
1909. Yachting on the Pacific. London, 286 pp.
- MANSFIELD, G. R., AND L. BOARDMAN
1932. Nitrate deposits of the United States. *Bull. U. S. Geol. Surv.*, no. 838, 107 pp.
- MARCHAND, B. DE C.
1918. Note on the occurrence of a peculiar phosphate of aluminum in a deposit of bat guano. *South African Jour. Sci.*, vol. 15, pp. 638-639.
- MARCHAND, J. M.
1928. The nature of the sea-floor deposits in certain regions on the west coast. *Union of South Africa, Fish. and Marine Biol. Surv.*, rept. no. 6, spec. rept. no. 5.
- MARCHET, A.
1931. Chemische Untersuchung von Phosphaterden. In Abel, O., and G. Kyrle, Die Drachenhöhle bei Mixnitz. Vienna, (Verlag) Österr. Staatsdruckerei, Spelaeol. Monogr., vols. 7, 8, pp. 259-263.
- MARKHAM, C. R.
1862. Travels in Peru and India. London, J. Murray, xviii+572 pp.
1864. The travels of Pedro de Cieza de Leon, A.D. 1532-1550. London, Printed for the Hakluyt Society, 438 pp.
1880. Peru. London, Sampson Low, Marston, Searle, and Rivington, 192 pp.
- MARR, J. E.
1876. Note on the occurrence of phosphatised carbonate of lime at Cave Ha, Yorkshire. *Geol. Mag.*, dec. 2, vol. 3, pp. 268-269.
- MARTELLI, D.
1902. Dei Guani raccolti in alcune isole del Mar Rosso e nella Colonia Eritrea. *Att. R. Accad. econ.-agr. dei Georgofili di Firenze*, ser. 4, vol. 25, whole vol. 80, pp. 21-37.

- MARTIN, K.
1879. Phosphoritische Kalke von der west-indischen Insel Bonaire. *Zeitschr. Deutsche Geol. Gesellsch.*, vol. 31, pp. 473-479.
1885. Ueber das Vorkommen von Dania auf Curaçao. *Neues Jahrb. Min. Geol.*, pt. 2, pp. 239-240.
1888. Bericht über eine Reise nach Niederländisch West-Indien und darauf gegründete Studien. Leiden, E. J. Brill, vol. 2, *Geologie*, 238 pp.
Phosphate, p. 88.
- MASCHHAUPT
1908. Onderzoek naar de Samenstelling von ruwe Peru-Guano. The Hague.
Not seen; reference in Popp and Marxen, 1931.
- MATLEY, C. A.
1926. The geology of the Cayman Islands (British West Indies), and their relation to the Bartlett Trough. *Quart. Jour. Geol. Soc.*, vol. 82, pt. 3, pp. 352-386.
1928. Phosphate in the Cayman Islands. *Congr. Geol. internatl. Madrid, Réserve Mondiales en Phosphates*, vol. 2, pp. 777-779.
- MATTHEWS, D. J.
1926. Physical oceanography. Reports of the Percy Sladen Trust Expedition to the Indian Ocean in 1905. Vol. 8. *Trans. Linnean Soc. London*, ser. 2, (zool.), vol. 19, pp. 169-205.
- MATTINGLEY, A. H. E.
1908. A night with the birds of Laurence Rocks. *Victoria Nat.*, Melbourne, vol. 25, pp. 12-24.
1934. Notes on the potentialities of guano production in Australia. *Emu*, vol. 33, pp. 236-241.
- MAWSON, D., AND W. T. COOKE
1907. The phosphate minerals from Elder Rock. *Trans. Roy. Soc. Southern Australia*, vol. 31, pp. 65-70.
- MAYNARD, C. J.
1889. Description of a supposed new species of gannet. *Contrib. to Science*, vol. 1, pp. 40-48, 51-57.
- MAYOR, ALFRED G.
1924. Rose Atoll, American Samoa. *Papers Dept. Marine Biol., Carnegie Inst. Washington Publ.*, no. 340, vol. 19, pp. 73-92. Also *Proc. Amer. Phil. Soc.*, 1921, vol. 60, pp. 62-70.
- MAYR, E.
1941. List of New Guinea birds. New York, the American Museum of Natural History, 260 pp.
1945. Birds of the southwest Pacific. New York, Macmillan and Co., 316 pp.
1946. The number of species of birds. *Auk*, vol. 63, pp. 64-70.
- MEHMEL, MARTIN
1930. Über die Struktur des Apatits, I. *Zeitschr. Krist.*, vol. 75, pp. 323-331.
- MEINERTZHAGEN, R.
1930. Nicoll's birds of Egypt. London, Hugh Rees, Ltd., vol. 1, pp. 1-348; vol. 2, pp. 349-700.
- MEINICKE, K. E.
1875-1876. Die Inseln des Stillen Oceans, eine geographische Monographie. Leipzig, Paul Froberg, vol. 1, 1875, 382 pp.; vol. 2, 1876, 487 pp.
- MEISE, W.
1938. Guano und anderer Vogeldung. In Pax, F., and W. Arndt, *Die Rohstoffe des Tierreichs*. Berlin, Borntraeger, vol. 1, pt. 2, pp. 2113-2172.
- MERCER, HENRY C.
1897. The finding of the remains of the fossil sloth at Big Bone Cave, Tennessee, in 1896. *Proc. Amer. Phil. Soc.*, Philadelphia, vol. 36, pp. 36-70.
- MEYEN, F. J. F.
1834-1835. Reise um die Erde ausgeführt auf dem königlich preussischen Seehandlungs-Schiffe Prinzess Louise, commandirt von Capitain W. Wendt in den Jahren 1830, 1831 und 1832. *Historischer Bericht*, Berlin, Sander'sche Buchhandlung, 2 vols.
- MEYERHOFF, H. A.
1933. Geology of Puerto Rico. *Univ. Puerto Rico Monogr.*, ser. B, phys. and biol. sci., no. 1, 306 pp.
- MEYN, L.
1879. Das Phosphorit-Lager von Curacao. *Zeitschr. Deutsche Geol. Gesellsch.*, vol. 31, pp. 697-704.
Analyses apparently quoted from Gilbert, 1877, *Göttingen Jour. f. Landw.*, vol. 10, p. 418.
- MIDDENDORF, E. W.
1894. Peru. Berlin, R. Oppenheim (Gustav Schmidt), 425 pp.
- MILLER, C. F.
1914. On the composition and value of bat guano. *Jour. Indust. Engin. Chem.*, vol. 6, pp. 664-665.
- MILLER, GERRITT S., JR.
1912. Catalogue of the mammals of western Europe (Europe exclusive of Russia). London, British Museum (Natural History), xv+1019 pp.
1929. Mammals eaten by Indians, owls and

- Spaniards in the coast region of the Dominican Republic. Smithsonian Misc. Coll., vol. 82, no. 5, 16 pp.
- MILLER, GERRITT S., JR., AND GLOVER M. ALLEN
1928. The American bats of the genera *Myotis* and *Pisonyx*. Bull. U. S. Natl. Mus., no. 144, viii+218 pp.
- MILLER, GERRITT S., JR., AND HERBERT W. KRIEGER
1929. Expedition to Samaná Province, Dominican Republic. Exploration and field work of the Smithsonian Institution in 1928, pp. 43-54.
- MINDER, L. P.
1933. Fishery and fish cultivation of the Azov Sea basin. Trans. Res. Inst. Fisheries (USSR), vol. 3, 3. (Promisel i obrabotka ribi Azovskovo basseina. Trudi Vses. Naukno Issl. Inst. Ribnoi promishl. T, III, 3, 1933.)
- MINENBUREAU
1928. Phosphatlagerstaetten in Niederlaendisch Indien. Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates, vol. 2, pp. 553-555.
- MINGAYE, JOHN C. H.
1898a. On the occurrence of phosphatic deposits in the Jenolan Caves, New South Wales. Rept. Australasian Assoc. Adv. Sci., vol. 7, pp. 327-331.
1898b. Notes and analyses of some New South Wales phosphatic minerals and phosphatic deposits. *Ibid.*, vol. 7, pp. 332-333.
- MITCHELL, L., G. T. FAUST, S. B. HENDRICKS, AND D. S. REYNOLDS
1943. The mineralogy and genesis of hydroxylapatite. Amer. Min., vol. 28, pp. 356-371.
- MITCHELL, SIR THOMAS L.
1839. Three expeditions into the interior of eastern Australia. Second edition. London, T. and W. Boone, vol. 2, 415 pp. Wellington caves, pp. 359-372.
- MÖLLER, L.
1929. Die Zirkulation des Indischen Ozeans auf Grund von Temperatur- und Salzgehaltstiefenmessungen und Oberflächenströmbeachtungen. Veröffentlich. Inst. f. Meereskunde, Berlin Univ., new ser., geogr.-naturwiss. ser., vol. 21, 48 pp.
- MOHR, CHARLES E.
1932. *Myotis grisescens* and *Myotis sodalis* in Tennessee and Alabama. Jour. Mammal., vol. 13, pp. 272-273.
1933. Observations on the young of cave-dwelling bats. *Ibid.*, vol. 14, pp. 49-53.
- MOLENGRAAFF, G. J. H.
1931. Curaçao. Leidsche Geol. Meded., vol. 5, pp. 673-689.
- MONTGOMERY, R. B.
1941. Transport of the Florida current off Habana. Jour. Marine Res., vol. 4, pp. 198-220.
- MOORE, E.
1926. El Cormoran (guanay o yeco). Rev. Chilena Hist. Nat., vol. 30, pp. 176-183.
- MOORE, G. E.
1865. On brushite, a new mineral occurring in phosphatic guano. Amer. Jour. Sci., vol. 39, pp. 43-44.
- MOREAU, R. E.
1940. Contributions to the ornithology of the east African islands. Ibis, ser. 14, vol. 4, pp. 48-91.
- MORFIT, C.
1855. On Colombian guano, and on certain peculiarities in the chemical behaviour of bone-phosphate of lime. Chem. Gaz., vol. 13, pp. 451-456.
- MORGAN, P. G.
1915. Phosphate occurrences in the South Island, New Zealand. 9th Ann. Rept., Geol. Surv. Branch, new ser., pp. 97-98.
1928. Phosphates in New Zealand. Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates, vol. 2, pp. 823-827.
- MORRELL, B.
1832. A narrative of four voyages to the South Seas, north and south Pacific Ocean, Chinese Sea, Ethiopic and southern Atlantic Ocean, Indian and Antarctic Ocean. From the year 1822 to 1831. New York, 492 pp.
1852. Morrell's narrative of a voyage to the south and west coast of Africa: containing the information from whence originated the present trade in guano found on certain islands of that coast. With a prefatory advertisement by Lieut. Petrie, R. N. and an appendix. London, Whittaker and Co., Liverpool, Grapel, vii+144 pp.
- MOSER, J.
1878. Ueber verschiedene Düngstoffe. Erster Ber. über Arbeiten d. K. K. Landw. Chem. Versuchst. in Wien, Jahren 1870-1877.
Original not seen; abstract in Jahresb. Agr. Chem., 1879, new ser., vol. 2, pp. 275-276.
- MUNTZ, A., AND V. MARCANO
1887. Sur la formation des terres nitrées dans les régions tropicales. Ann. Chim. et Phys., ser. 6, vol. 10, pp. 550-566.

- MURCHISON, R. I.
1859. On the commercial and agricultural value of certain phosphatic rocks of the Anguilla Isles in the Leeward Islands. Jour. Roy. Agr. Soc., ser. 1, vol. 20, pp. 31-32.
- MURPHY, R. C.
1920. Seacoast and islands of Peru. Brooklyn Mus. Quart., vol. 7, I in no. 2, pp. 69-95; II in no. 3, pp. 165-187; III in no. 4, pp. 239-272.
1921. Seacoast and islands of Peru. *Ibid.*, vol. 8, IV in no. 1, pp. 1-28; V in no. 2, pp. 35-57; VI in no. 3, pp. 91-106; VII in no. 4, pp. 142-155.
1923. The oceanography of the Peruvian littoral with reference to the abundance and distribution of marine life. Geogr. Rev., vol. 13, pp. 64-85.
1924. The Whitney South Sea expedition. Nat. Hist., vol. 24, no. 5, pp. 539-553.
1925. Bird islands of Peru. New York, G. P. Putnam's Sons, 362 pp.
1926. Oceanic and climatic phenomena along the west coast of South America during 1925. Geogr. Rev., vol. 16, pp. 26-54.
1927. The Peruvian guano islands seventy years ago. Nat. Hist., vol. 27, pp. 439-447.
1936. Oceanic birds of South America. New York, the American Museum of Natural History, 2 vols., 1245 pp.
1944. More about Peruvian fisheries. Geogr. Rev., vol. 34, pp. 141-142.
- MURPHY, R. C., AND G. M. MATHEWS
1929. Birds collected during the Whitney South Sea expedition. VI. (Sylviidae). Amer. Mus. Novitates, no. 350, pp. 1-21.
- NÁRAY-SZABÓ, ST.
1930. The structure of apatite $(\text{CaF})\text{Ca}_4(\text{PO}_4)_3$. Zeitschr. f. Kristallographie, vol. 75, pp. 387-398.
- NASH, [ALANSON] C.
1856. Guano. Trans. Amer. Inst., pp. 217-218.
- NEEDHAM, JOSEPH
1931. Chemical embryology. Cambridge, England, the University Press, 3 vols.
- NELSON, E. W.
1899. Birds of the Tres Marias Islands. North American Fauna, no. 14, U. S. Dept. Agr., Div. Biol. Surv., pp. 21-62.
1926. Bats in relation to the production of guano and the destruction of insects. Bull. U. S. Dept. Agr., no. 1395, 12 pp.
- NESBIT, J. C.
1860. The history and properties of the different varieties of natural guanos. A new edition. London, Rogerson and Tuxford, 50 pp.
- NEWTON, E. T.
1890. Note on the bones of small birds obtained by Professor Nation from below the nitrate-beds of Peru. Proc. Zool. Soc. London, pp. 375-376.
- NICHOLS, HENRY W.
1901. Nitrates in cave earth. Jour. Geol., vol. 9, p. 236.
- NOMURA, S., AND N. ZINBÔ
1934. Marine Mollusca from the "Ryûkyû Limestone" of Kikai-Zima, Ryûkyû group. Sci. Rept. Tôhoku Imp. Univ., Sendai, Japan, (geol.), ser. 2, vol. 16, pp. 109-164.
1935. Fossil and recent Mollusca from the island of Kita-Daitô-Zima. *Ibid.*, (geol.), ser. 2, vol. 18, pp. 41-51.
- NORIEGA DEL AGUILA, M.
1939. Presence of sterols in Peruvian guano. Bol. Soc. Quím. Peru, 1938, vol. 4, pp. 199-200.
- NORTH, A. J.
1908. On three apparently undescribed birds from Henderson or Elizabeth Island, Paumotu group. Rec. Australian Mus., vol. 7, pp. 29-32.
1912. Nests and eggs of birds found breeding in Australia and Tasmania. Sydney, Australian Mus., special cat. no. 1, vol. 3, 362 pp.
1914. Nests and eggs of birds found breeding in Australia and Tasmania. Sydney, Australian Mus., special cat. no. 1, vol. 4, 472 pp.
Note: vol. 3 was issued in parts 1911-1912; vol. 4, in parts 1913-1914. The dates given in the reference refer to the parts containing the Sulidae (1912) and the other relevant sea birds (1914), respectively.
- NORTH, MAJOR M. E. W.
1946. Mait Island—a bird-rock in the Gulf of Aden. Ibis, vol. 88, pp. 478-501.
- NOYES, F. C.
1944. Phosphate rock industry of foreign countries. Mining and Metallurgy, vol. 25, pp. 495-506.
- NUGENT, L. E.
1948. Elevated phosphate islands in Micronesia. Bull. Geol. Soc. Amer., vol. 59, pp. 977-994.
- NYE, P. B.
1928. Phosphate in Tasmania. Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates, vol. 2, pp. 831-832.

- OCHSENIUS, C.
1887. Die Bildung des Natronsalpeters aus Mutterlaugensalzen. Stuttgart.
Not seen; reference in Wetzel, W., 1930, *q.v.*
- OGILVIE-GRANT, W. R.
1913. On a small collection of birds from Henderson Island, south Pacific. *Ibis*, ser. 10, no. 3, pp. 343-350.
- OINOUE, Y.
1928. Phosphates of Japan. Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates, vol. 2, pp. 559-562.
- ORCEL, J.
1918. Note sur la composition de la phosphorite de l'île Juan de Nova (Madagascar). *Bull. Soc. Française Min.*, vol. 41, pp. 104-108.
- ORR, A. P.
1933. Physical and chemical conditions in the sea and neighborhood of the Great Barrier Reef. *Sci. Rept. Great Barrier Reef Expedition, 1928-1929*, Brit. Mus. Nat. Hist., vol. 2, no. 3, pp. 37-86.
- OSBURN, W.
1865. Notes on the Chiroptera of Jamaica. *Proc. Zool. Soc. London*, pp. 61-85.
- OSORIO TAFALL, B. F.
1943. El mar de Cortés y la productividad fitoplanctónica de sus aguas. *An. Escuela Nac. Cien. Biol.*, Mexico, vol. 3, nos. 1-2, pp. 73-118.
1944. La Expedición del M. N. "Gracioso" por aguas del extremo noroeste mexicano. *Ibid.*, vol. 3, nos. 3-4, pp. 331-360.
- OWEN, L.
1923. Notes on the phosphate deposit of Ocean Island; with remarks on the phosphates of the equatorial belt of the Pacific Ocean. *Quart. Jour. Geol. Soc. London*, vol. 79, pp. 1-15.
1927. The phosphate deposits on Ocean Island. *Econ. Geol.*, vol. 22, pp. 632-634.
- OWEN, SIR RICHARD
1845. A history of British fossil mammals and birds. London, John van Voorst., 560 pp.
1877. Researches on the fossil remains of the extinct mammals of Australia. London, J. Erxleben, vol. 1, 522 pp.
- OWEN, W. F. W.
1833. Narrative of voyages to explore the shores of Africa, Arabia and Madagascar. New York, J. and J. Harper, vol. 1, 260 pp.
1857. The coast of Arabia Felix,—from the journal of Capt. W. F. W. Owen of H.M.S. "Leven." *Nautical Mag.*, vol. 26, pp. 180-191.
- PACIFIC GUANO COMPANY
1876. The Pacific Guano Company; its history; its products and trade; its relation to agriculture. Cambridge, Riverside Press, 63 pp.
- PAECH, H.
1926. Die Oberflächenströmungen um Madagaskar in ihrem jährlichen Gang. *Veröffentl. Inst. f. Meereskunde, Berlin Univ.*, new ser. 2, geogr.-naturwiss. ser., vol. 16, 39 pp.
- PAGE, JOHN L.
1930. Climate of Mexico. Washington, D. C., United States Department of Agriculture, Weather Bureau, Monthly Weather Review Suppl., no. 33, 30 pp.
- PAKENHAM, R. H. W.
1943. Field notes on the birds of Zanzibar and Pemba. *Ibis*, vol. 85, pp. 165-189.
- PALACHE, CHARLES
1923. A new mode of occurrence of struvite. *Amer. Min.*, vol. 8, pp. 72-73.
- PALMER, H. S.
1927. Geology of Kaula, Nihoa, Necker, and Gardner Islands, and French Frigate Shoal. *Bull. Bernice P. Bishop Mus.*, no. 35, 35 pp.
- PALMER, T. S.
1900. A review of economic ornithology in the United States. *Yearbook, U. S. Dept. Agr.*, for 1899, pp. 259-292.
- PANNEKOEK VAN RHEDEN, J. J.
1913. Overzicht van de geographische en geologische gegevens, verkregen bij de Mijnbouwkundig-geologische verkenning van het Eiland Flores in 1910 en 1911. *Jaarb. van het Mijnwezen in Nederlandsch Oost-indië*, 40th year, 1911; *verhandel.*, pp. 208-226.
- PARIS, GIULIO
1897. Su un guano rinvenuto nelle vicinanze di Eboli (Salerno). *Staz. Sperim. Agrarie Italiane*, vol. 30, pp. 132-138.
1899. Su un nuovo guano di pipistrelli trovato a Cagliari (Sardegna). *Ibid.*, vol. 32, pp. 176-195.
- PARR, ALBERT EIDE
1937. A contribution to the hydrography of the Caribbean and Cayman seas. *Bull. Bingham Oceanogr. Coll.*, vol. 5, art. 4, 110 pp.
- PAX, F.
1938. Zoogene Bau- und Schottermaterialien rezenten Ursprungs (Termiten). *In Pax, F., and W. Arndt, Die Rohstoffe des Tierreichs*. Berlin, Borntraeger, vol. 1, pt. 2, pp. 2069-2070.

- PEACOCK, GEORGE
1874. The resources of Peru. Third edition. Exeter, England, 74 pp.
- PECK, GEORGE WASHINGTON
1854. Melbourne and the Chincha Islands; with sketches of Lima and a voyage round the world. New York, Charles Scribner, 294 pp.
- PENROSE, F. G.
1879. Notes on a collection of birds' skins and eggs made by Mr. D. Gill, F.R.A.S., on Ascension Island. *Ibis*, ser. 4, vol. 3, pp. 272-282.
- PETERMANN, A.
1888. [Der Fledermausguano von der Insel Cuba.] *Bull. Sta. Agr. à Gembloux*, no. 42, pp. 1-5.
Not seen; *abstract in* *Chem. Centralbl.*, 1888, vol. 59 (ser. 3, vol. 19), p. 1438.
- PETERS, E.
1873. Analyse. *Wochenbl. d. Landw. Ver. in Baden*, p. 38.
Abstract in *Jahresb. Agr. Chem.*, 1877, 16-17 Jahrg., vol. 3, p. 23.
- PETERS, J. L.
1931. Check-list of the birds of the world. Cambridge, Harvard University Press, vol. 1, 345 pp.
1934. Check-list of the birds of the world. Cambridge, Harvard University Press, vol. 2, 401 pp.
1937. Check-list of the birds of the world. Cambridge, Harvard University Press, vol. 3, 311 pp.
- PHILADELPHIA GUANO COMPANY
1856a. Columbian guano brought from the guano islands in the Caribbean Sea, belonging to the republic of Venezuela. Philadelphia, Printing rooms of James H. Bryson, 15 pp.
Trade pamphlet.
1856b. Columbian and other phosphatic guanos. Philadelphia, McLaughlin Brothers, 16 pp.
Trade pamphlet.
- PHILIPPI, R. A.
1895. Über einige Vogelknochen aus dem Guano. *Verhandl., Deutschen Wiss. Ver.*, Santiago, vol. 3, pt. 1, pp. 14-17.
- PHILLIPS, W. B.
1901. The bat guano caves of Texas. *Mines and Minerals*, vol. 21, pp. 440-492.
- PHIPSON, T. L.
1862a. On the presence of xanthic oxide in guanos containing no uric acid. *Chem. News*, vol. 6, p. 16.
1862b. *Sombrierite*. *Jour. Chem. Soc. London*, vol. 15, p. 277.
1863. Note on the bicarbonate of ammonia of the Chincha Isles. *Ibid.*, vol. 16, pp. 74-76.
- PHOENIX GUANO COMPANY (WILLIAMS, HAVEN AND COMPANY, AGENTS)
1860. Phoenix guano from McKean's Island, Pacific Ocean, imported by the Phoenix Guano Company. Analysis by S. W. Johnson, Yale. New London, Starr and Farnham, 8 pp.
1871. Phoenix guano from Pacific Ocean, imported by the Phoenix Guano Company. New London, Starr and Farnham, 20 pp.
Trade pamphlet.
- PICKETT, J. C.
1848. Letters and dissertations upon sundry subjects. Washington, William Greer, 64 pp.
Guano, pp. 34-40.
- PICKFORD, G. E.
1937. A monograph of the acanthodriline earthworms of South Africa. Cambridge, England, W. Heffer and Sons, Ltd., 612 pp.
- PIGGOT, A. SNOWDEN
1857. Hard guano of Monks Island. *Amer. Jour. Sci.*, ser. 2, vol. 23, pp. 120-121.
- PIPJERS, P. J.
1933. Geology and paleontology of Bonaire (D. W. I.). *Geogr. Geol. Meded. Utrecht*, vol. 8, 103 pp.
- POOLE, ARTHUR J.
1929. Further exploration of Haitian caves. Exploration and field-work of the Smithsonian Inst., in 1928, pp. 55-62.
- POPP, M., AND J. MARXEN
1931. Neue Untersuchungen über den Guano. *Landw. Versuchs-Stationen*, vol. 112, pp. 261-312.
- POPP, O.
1870. Ueber die Zusammensetzung der Excremente von ägyptischen Fledermäusen. *Ann. d. Chemie (Liebig's Annalen)*, vol. 155, pp. 351-355.
1871. Ueber die Excremente der gemeinen Fledermaus. *Ibid.*, vol. 158, pp. 115-116.
- PORTENKO, L.
1931. Les ressources productives de l'ornithofaune de la Nouvelle-Zemble. [In Russian.] *Trudy Biogeokhimicheskai Lab. Akad. Nauk, Leningrad*, vol. 2, Suppl., 52 pp. 13 figs.
- PORTER, M. W.
1924. Note on occurrence of struvite. *Amer. Min.*, vol. 9, pp. 93-94.
- POWER, F. DANVERS
1905. Phosphate-deposits of Ocean and Pleas-

- ant Islands. Trans. Australian Inst. Min. Engin., vol. 10, no. 137, pp. 213-232.
1925. Phosphate deposits of the Pacific. Econ. Geol., vol. 20, pp. 266-281.
- PRIVAT-DESCHANEL, PAUL
1910. Les gisements de guano et de phosphates de l'océan Pacifique. Le Génie Civil, vol. 57, pp. 47-50.
- PRYER, H.
1884. An account of a visit to the bird-nest caves of British North Borneo. Proc. Zool. Soc. London, pp. 523-538.
- PUENTE, J. R. DE LA
1933. El guano pobre. Bol. Compañía Administradora Guano, Lima, vol. 9, no. 7, pp. 169-211.
- PURCELL, C. S., AND C. H. HICKEY
1922. Note on an occurrence of struvite in canned shrimps. Analyst, London, vol. 47, pp. 16-18.
- RADIGUET, M. R.
1856. Souvenirs de l'Amérique Espagnole: Chili-Pérou-Brésil. Paris, M. Lévy Frères, 308 pp.
- RAIMONDI, A.
1856. Mémoire sur le guano de îles de Chincha et les oiseaux qui le produisent. Compt. Rendus Acad. Sci., Paris, vol. 42, pp. 735-738.
1873. La manipulacion del guano. Lima, Imprenta de "el Nacional" por Pedro Lira, 29 pp. Reprinted in Bol. Compañía Administradora Guano, Lima, 1926, vol. 2, no. 9, pp. 468-500.
1874. Guano (Nouveaux dépôts). In Guanos de Tarapaca, documents officiels anglais and péruviens, publiés par la légation du Pérou en France. Paris, Librairie général, pp. 11-15.
1876. El Peru. Lima, Imprenta del estado, vol. 2, 475 pp.
1878. Minéraux du Pérou, catalogue raisonné d'une collection des principaux types minéraux de la République comprenant aussi des échantillons de guano et des débris fossilisés des oiseaux qui l'ont produit. Trad. J. B. H. Martinet. Paris, A. Chaix et Cie, 336 pp.
1897. Islas, islotas y rocas del Peru. Bol. Soc. Geogr., vol. 7, nos. 7, 8, and 9, 11 pp. Reprinted in Bol. Compañía Administradora Guano, Lima, 1926, vol. 2, no. 9, pp. 455-468.
- RAKESTRAW, N. W., AND H. P. SMITH
1937. A contribution to the chemistry of the Caribbean and Cayman seas. Bull. Bingham Oceanogr. Coll., vol. 6, art. 1, pp. 1-41.
- RAMSEY, W. G.
1925. Meteorological conditions on Baker and Howland Islands. Monthly Weather Rev., vol. 53, no. 1, pp. 23-24.
- RANGE, P.
1912. Geologie des deutschen Namalandes. Berlin, Im Vertrieb der Königlich preussischen geologischen Landesanstalt, 104 pp.
- RATH, W. VOM
1878. Mehrere durch Herrn Ulrich dem Universitätsmuseum verehrten Mineralien. Sitzungsber. Niederrheinischen Gesellschaft. Bonn, 1878, pp. 8-12.
1879. Ueber den Hannayit und den Newberyit. *Ibid.*, 1879, pp. 5-9.
- REED, W. W.
1926. Climatological data for the West Indian Islands. Monthly Weather Rev., vol. 54, pp. 133-160.
1927. Climatological data for the tropical islands of the Pacific Ocean (Oceania). *Ibid.*, suppl. 28, pp. 1-22.
1928. Climatological data for northern and western tropical South America. *Ibid.*, suppl. 31, pp. 1-21.
- REINHARDT, J.
1888. De brasilianski Knoglehuler og de i dem forekommende Dyreleevninger. E Museo Lundii: En Samling af Afhandlinger de i det indre Brasiliens Kalkstenshuler af Professor Dr. Peter Vilhelm Lund, etc. Copenhagen, vol. 1, art. 1, 56 pp.
- REINOSO, D. ALVARS [sic]
1859. Informe sobre el guano en los cayos de los Jardinillos adyacentes a la Isla de Cuba. Madrid.
- Also issued as Rapport sur le guano de Cayes de los Jardinillos. Paris, 1859. Originals not seen; titles in Jahresber. Agr. Chem., 1861, vol. 2, pp. 244, 246.
- RICHARDS, G.
1928. Newberyite and other phosphates from Ascension Island. Amer. Min., vol. 13, pp. 397-401.
- RICHARDSON, CHARLES HENRY
1925. Mineralogy of Kentucky. Kentucky Geol. Surv., ser. 7, vol. 27, 170 pp.
- RITTHAUSEN
1863. Landw. Jahrb. aus Ostpreussen, p. 226.
- Not seen; reference in Heiden, 1887.
- RIVERO (Y USTARIZ), MARIANO EDUARDO DE [ALSO OFTEN SPELLED RIBERO]
1827. Memoria sobre el guano de pájaros del Peru.
- Original edition not seen. *Reprinted*

- in* Rivero: Coleccion de memorias cientificas, agricolas é industriales. Brussels, 1857, vol. 1, pp. 159-171. Tschudi (1846a) and Murphy (1936) record a work of the same author with the title: Memoria sobre el guano de pájaros y su uso en el Perú. Lima, 1837. This, if it exists, may be a later and possibly amplified edition of the work issued in 1827. Another revision appears to have been published in 1845 and reprinted with additions in 1852, as indicated below.
1828. Razon de las haciendas del valle de Chancay y las cantidades de fanegas de guano que él en el beneficio de sus tierras por año, sacado de las islas de Chincha y de Ancon. *In* Rivero and Pierola: Memoria de ciencias naturales y de industria nacional y extranjera. Lima, vol. 1, no. 2, p. 70.
Original edition not seen. Reprinted in Rivero: Coleccion de memorias etc., vol. 1, p. 171.
1852. Estudios sobre el Huano. El Interprete del Pueblo, Jan. 23, 26, and 27, 1852.
Original edition not seen, reprinted in both the original Spanish (pp. 51-64) and in English translation (pp. 64-71) as an enclosure in letter no. 32 (Rivero to the Earl of Malmesbury, London, 4 May, 1852) *in* Great Britain, Parliamentary Sessional Papers, 1852, vol. 54.
The three articles are stated by Rivero to be abridged from a pamphlet, which at the time of writing was being reprinted in Lima. This is said to have been based on a revised Memoria published by Rivero in 1845. In addition, material on the islands north of Pisco Bay, obtained in 1847 by Edward O. Carter (so designated on the plates; Rivero spells the name Cater throughout) is incorporated. Such material has been referred to as Carter *in* Rivero (1852). The formal notes on birds given in the Estudios are expressly credited to Raimondi. It is presumably correct to suppose that all the other material is derived from Rivero's writings, mainly the 1845 Memoria. The Estudios were submitted to the Earl of Malmesbury as evidence for Peruvian claims of sovereignty over the Lobos Islands which certain British guano merchants and agriculturalists wished the British Government to annex.
- RIVIÈRE, A.
1939a. Sur la dolomitisation des sédiments calcaires. Compt. Rendus Acad. Sci., Paris, vol. 209, pp. 597-599.
- 1939b. Observations nouvelles sur le mécanisme de dolomitisation des sédiments calcaires. *Ibid.*, vol. 209, pp. 691-692.
- ROBERTS, BRIAN
1940a. The life cycle of Wilson's petrel, *Oceanites oceanicus* (Kuhl). Brit. Graham Land Exped., 1934-1937, Sci. Repts., vol. 1, no. 2, pp. 141-194.
1940b. The breeding behavior of penguins with special reference to *Pygoscelis papua* (Forster). *Ibid.*, vol. 1, no. 3, pp. 195-254.
- ROBINSON, W. O.
1948. The presence and determination of molybdenum and rare earths in phosphate rock. Soil Sci., vol. 66, no. 4, pp. 317-322.
- ROCK, J. F.
1916. Palmyra Island with a description of its flora. Bull. College of Hawaii, vol. 4, 53 pp.
- RODGERS, JOHN
1948. Phosphate deposits of the former Japanese islands in the Pacific; a reconnaissance report. Econ. Geol., vol. 43, pp. 400-407.
- RÖMER, FERDINAND
1884. The bone caves of Ojcow in Poland. Trans. John Edward Lee. London, Longmans, Green and Co., 41 pp., 12 pls.
- ROGERS, A. F.
1922. Collophane, a much neglected mineral. Amer. Jour. Sci., ser. 5, vol. 3, pp. 269-276.
- ROSE, H.
1862. Ueber die Zusammensetzung eines fossilen Eies. Poggendorff's Ann., vol. 117, pp. 627-629.
- ROST, M.
1938. Die venezolanischen Inseln Las Aves, Los Roques, Las Orchilas und die Phosphoritlagerstätte von Gran Roque. Zeitschr. Deutsche Geol. Gesellsch., vol. 90, pp. 577-596.
- ROTH, S.
1899. Descripción de los restos encontrados en la caverna de Ultima Esperanza. *In* Hauthal, R., S. Roth, and R. Lehmann-Nitsche, El Mamífero Misterioso de la Patagonia, "Gryotherium domesticum." Rev. Mus. de la Plata, vol. 9, pp. 421-453.
- ROTHSCHILD, LIONEL WALTER, BARON
1893-1900. The avifauna of Laysan and the neighbouring islands; with a complete history to date of the birds of the

- Hawaiian possessions. London, R. H. Porter.
1915. On the gigantic land tortoises of the Seychelles and Aldabra-Madagascar group with some notes on certain forms of the Mascarene group. *Novitates Zool.*, vol. 22, pp. 418-442.
- RÓZSA, M.
1917. Fledermausguanolager in der Umgebung von Budapest. *Naturwiss. Wochenschr.*, new ser., vol. 16, pp. 434-435.
- RUTTEN, L.
1931. On rocks from the Venezuelan islands between Bonaire and Trinidad and on some rocks from northwestern Venezuela. *Proc. Sect. Sci., Roy. Acad. Amsterdam*, ser. 2, vol. 34, pp. 1101-1110.
- St. JOHN, H., AND F. R. FOSBERG
1937. Vegetation of Flint Island, central Pacific. *Occas. Papers Bernice P. Bishop Mus.*, vol. 12, no. 24, pp. 51-52.
- St. JOHNSTON, T. R.
1920. The Falkland Islands. Stanley, F. I., 100 pp.
Not seen; reference in Murphy, 1936.
- SALVADORI, T.
1895. Catalogue of the Chenomorphae, Crypturi, and Ratitae in the collection of the British Museum. London, British Museum (Natural History), vol. 27, 636 pp.
- SANDELL, E. B., M. H. HEY, AND DUNCAN MCCONNELL
1939. The composition of francolite. *Min. Mag.*, vol. 25, pp. 395-401.
- SANDLAND, P. T.
1937. Notes on birds on Pelsart Island. *Emu*, vol. 37, pp. 144-149.
- SCHADLER, JOSEPH
1920. Die Phosphatablagerungen in der Lettenmayerhöhle bei Kremsmünster in Oberösterreich. *Berichte der staatlichen Höhlen-kommission. Spelaeol. Jahrb.*, Vienna, vol. 1, pp. 26-31.
1931. Die Ablagerungen. In Abel, O., and G. Kyrle, Die Drachenhöhle bei Mixnitz. Vienna, (Verlag) Österr. Staatsdruckerei, Spelaeol. Monogr., vols. 7, 8, pp. 169-224.
1932. Ardealite, ein neues mineral. $\text{CaHPO}_4 \cdot \text{CaSO}_4 + 4\text{H}_2\text{O}$. *Zentralb. Min. Geol. Paleont.*, ser. A, pp. 40-41.
- SCHADLER, JOSEPH, AND W. ARMBRECHT
1931. Brushit und Kollophan. In Abel, O., and G. Kyrle, Die Drachenhöhle bei Mixnitz. Vienna, (Verlag) Österr. Staatsdruckerei, Spelaeol. Monogr., vol. 7, 8, pp. 273-275.
- SCHADLER, JOSEPH, AND H. LIEB
1931. Scharizerit. In Abel, O., and G. Kyrle, Die Drachenhöhle bei Mixnitz. Vienna, (Verlag) Österr. Staatsdruckerei, Spelaeol. Monogr., vols. 7, 8, pp. 264-272.
- SCHAUINSLAND, H.
1899. Drei Monate auf einer Koralleninsel, (Laysan). *Abstract in Biol. Zentralbl.*, vol. 19, p. 622.
Also published separately, Bremen, 1899, 104 pp.
- SCHIEBLER
1872. *Annal. d. Landw.*, p. 709.
Not seen; reference in Jahresb. Agr. Chem., 1874, 13-15 Jahrg., vol. 1, p. 173.
- SCHMIDT, A.
1883. Newberyit von Mejillones, Chile. *Zeitschr. Krist.*, vol. 7, pp. 26-35.
- SCHMIDT, K. P.
1921. The herpetology of Navassa Island. *Bull. Amer. Mus. Nat. Hist.*, vol. 44, pp. 555-559.
1926. The amphibians and reptiles of Mona Island, West Indies. *Field Mus. Nat. Hist.*, zool. ser., vol. 12, pp. 149-163.
- SCHMITT, W. L.
1939. Decapod and other Crustacea collected on the Presidential cruise of 1938 (with introduction and station data). *Smithsonian Misc. Coll.*, vol. 98, no. 6, 29 pp.
- SCHNEIDER, OSCAR
1895. Carl Ribbe's Reisen in der Südsee. *Deutsche Geogr. Blätter*, vol. 18, pp. 372-386.
- SCHOTT, G.
1931. Der Perú Strom und seine nordlichen Nachbargebiete in normaler und anormaler Ausbildung. *Ann. Hydrogr. u. Marit. Met.*, vol. 59, pt. 5, pp. 161-169; pt. 6, pp. 200-213; pt. 7, pp. 240-252.
1935. *Geographie des Indischen und Stillen Ozeans*. Hamburg, C. Boysen, 413 pp.
- SCHROEDER, J.
1915. La composición de los guanos de murciélagos del Uruguay. *Rev. Asoc. Rural del Uruguay*, vol. 44, pp. 529-531.
- SCHUCHERT, C.
1935. Historical geology of the Antillean-Caribbean region, or the lands bordering the Gulf of Mexico and the Caribbean Sea. New York, J. Wiley and Sons, 811 pp.
- SCHUCHT, L.
1900. Ueber Phosphate. Leipzig, 33 pp.
- SCHULTZE, LEONHARD
1907. Die Fischerei an der Westküste Südafrikas. *Abhandl. Deutschen Seefisch.-Ver.*, vol. 9, 57 pp.
Guano, pp. 49-56.

- SCHWARZ, H.
1876. Analyse von Fledermaus-Guano. *Dingler's Polytech. Jour.*, vol. 218, p. 215. *Abstract in Jour. Chem. Soc.*, 1876, vol. 29, p. 730.
- SCHWEIGGER, E. H.
1931a. Observaciones oceanográficas sobre la corriente de Humboldt. *Bol. Compañía Administradora Guano, Lima*, vol. 7, no. 1, pp. 3-39.
1931b. Temperaturas en las islas guaneras del Perú (1926-1930). *Ibid.*, vol. 7, no. 3, pp. 121-143.
1940. Studies of the Peru coastal current with reference to the extraordinary summer of 1939. *Proc. Sixth Pacific Sci. Congr. Pacific Sci. Assoc.*, vol. 3, pp. 177-197.
1943. Pesquería y Oceanografía del Perú y Proposiciones para su Desarrollo futuro. [Spanish with English summary.] Lima, Gil, S. A. impresores, 356 pp.
- SEALE, R. F.
1834. The geognosy of the island St. Helena. London, Ackermann and Co., 25 pp.
- SEIDEL, H.
1891. Die Erforschung der Purdy-Inseln. *Globus*, vol. 59, pp. 303-304.
- SELLARDS, E. H., W. S. ADKINS, AND F. B. PLUMMER
1932. Stratigraphy. *Vol. 1 in The geology of Texas. Univ. Texas Bull.*, no. 3232, 1007 pp.
- SELM, F., AND G. MISSAGHI
1855. Analisi chimica del guano sardo. II *Nuovo Cimento*, vol. 2, pp. 25-41.
- SEMMES, DOUGLAS R.
1919. The geology of the San Juan district, Porto Rico. *New York Acad. Sci., Scientific Surv. Porto Rico and the Virgin Islands*, vol. 1, pp. 33-110.
- SESTINI, FAUSTO
1876. Analyse eines Fledermaus-Guano (Guano di Pipistrello). *Landw. Versuchs-Stat.*, vol. 19, pp. 10-11.
1895. Sul guano di Sardegna. *Atti R. Accad. Georgofili di Firenze*, vol. 73 (ser. 4, vol. 18), pp. 83-88.
- SETCHELL, W. A.
1924. Vegetation of Rose Atoll. *Part 3 of American Samoa. Dept. Marine Biol., Carnegie Inst. Washington*, vol. 20, pp. 225-261.
- SHARPE, R. B.
1900. Aves. In Andrews, C. W., A monograph of Christmas Island. London, British Museum (Natural History), pp. 37-50.
- SHARPLES, S. B.
1884. Turks Island and the guano caves of the Caicos Islands. *Proc. Boston Soc. Nat. Hist.*, vol. 22, pp. 242-252.
- SHAW, E. W., W. H. WRIGHT, AND J. L. DARNELL, JR.
1925. Mineral resources of Maranhão, Brazil. *Econ. Geol.*, vol. 20, pp. 723-728.
- SHEPARD, C. U.
1856. Five new mineral species. *Amer. Jour. Sci.*, ser. 2, vol. 22, pp. 96-99.
1869. On a mineral phosphate from the island of Redonda, W. I. *Ibid.*, ser. 2, vol. 47, pp. 428-429.
1870a. Redondite. *Ibid.*, ser. 2, vol. 50, p. 96.
1870b. Phosphoric acid in the diaspore of Chester, Mass. *Ibid.*, ser. 2, vol. 50, p. 96.
1870c. Notice of the Guanape Island guano. *Rural Carolinian*, vol. 1, pp. 469-471.
- SHEPARD, C. U., WITH ANALYSIS BY C. U. SHEPARD, JR.
1882. On two new minerals, monetite and monite with a notice of pyroclastite. *Amer. Jour. Sci.*, ser. 3, vol. 23, pp. 400-405.
- SHEPPARD, GEORGE
1930. Notes on the climate and physiography of southwestern Ecuador. *Geogr. Rev.*, vol. 20, pp. 445-453.
1932. The salt industry in Ecuador. *Ibid.*, vol. 22, pp. 403-410.
1933. The rainy season of 1932 in southwestern Ecuador. *Ibid.*, vol. 23, pp. 210-216.
- SICKENBERG, OTTO
1932. Die Säugetierfauna der Fuchs- oder Teufelstücken bei Eggenburg. *Verhandl. Zool.-Bot. Gesellsch. Wien, Ber. Sect. f. Paläont. und Abstammungslehre*, vol. 83, pp. (31)-(38).
- SIEVERS, W.
1898. Die Inseln vor der Nordküste von Venezuela (Nach den bisherigen Quellen un unter Berücksichtigung des Tagebuchs und der Gesteins-Sammlung Richard Ludwigs). *Globus*, vol. 74, pp. 163-165.
- SIMMONS, G. F.
1927. Sinbads of science: Narrative of a windjammer's specimen-collecting voyage to the Sargasso Sea, to Senegambian Africa and among islands of high adventure in the South Atlantic. *Natl. Geogr. Mag.*, vol. 52, no. 1, pp. 1-75.
- SIMPSON, E. S.
1932. Contributions to the mineralogy of Western Australia. *Jour. Roy. Soc. Western Australia*, ser. 7, vol. 18, pp. 61-74.

- SIMPSON, GEORGE GAYLORD
1930. Post-Mesozoic Marsupialia. In Pompeckj, J. F. (editor), *Fossilium catalogus. 1: Animalia*. Berlin, W. Junk, pt. 47, pp. 1-87.
- SKOTTSBERG, C.
1940. Report of the standing committee for the protection of nature in and around the Pacific for the years 1933-1938. *Proc. Sixth Pacific Sci. Congr. Pacific Sci. Assoc.*, vol. 4, pp. 499-542.
- SNODGRASS, R. E., AND E. HELLER
1902. The birds of Clipperton and Cocos Islands. *Proc. Washington Acad. Sci.*, vol. 4, pp. 501-520.
- SOHST
1878. *Annal. d. Hydrogr.*
Not seen; reference in Elschner, 1913, p. 183.
- SOLAR, DEL
1942. [Not seen, reference in Schweigger, 1942.]
- SORNAY, P. DE
1922. Le guano phosphate. *Rev. Agr. de l'Ile Maurice*, vol. 1, pp. 292-296.
- SPEIGHT, R., AND A. M. FINLAYSON
1909. Physiography and geology of the Auckland, Bounty and Antipodes Islands. In Chilton, C., *The Subantarctic Islands of New Zealand*. New Zealand, The Philosophical Institute of Canterbury, vol. 2, art. 30, pp. 505-744.
- SPEIGHT, W. L.
1940. The South African guano islands. *The Fertiliser, Feeding Stuffs and Farm Supplies Jour.*, vol. 25, pp. 242-243, 245.
- SPENCE, J. M.
1878. The land of Bolivar, or, war, peace and adventure in the republic of Venezuela. London, S. Low, Marston, Searle and Rivington, vol. 1, 323 pp.; vol. 2, 345 pp.
- STANLEY, C. S.
1874. [See Great Britain, Parliamentary Sessional Papers, 1874a, pp. 5-10.]
- STAPP, C.
1920. Botanische Untersuchung einiger neuer Bakterienspezies, welche mit reiner Harnsäure oder Hippursäure als alleinigem organischen Nährstoff auskommen. *Zentralbl. Bakt.*, ser. 2, vol. 51, pp. 1-71.
- STEERS, J. A.
1930. A geographical introduction to the biological reports. Great Barrier Reef Exped., 1928-1929, *Sci. Repts.*, vol. 3, no. 1, pp. 1-15.
- STEVENSON, W. B.
1825. A historical and descriptive narrative of twenty years' residence in South America. London, Hurst, Robinson and Co., 3 vols.
- STIGLICH, G.
1922. *Diccionario geográfico del Perú*. Lima, Impr. Torres Aguirre, 3 vols.
- STREETS, T. H.
1877a. Some account of the natural history of the Fanning group of islands. *Amer. Nat.*, vol. 11, pp. 65-72.
1877b. Contributions to the natural history of the Hawaiian and Fanning islands and Lower California. *Bull. U. S. Natl. Mus.*, no. 7, pp. 7-172.
- STRESEMANN, E.
1924a. *Oceanodroma hornbyi* (Gray) aus einem chilenischen Salpeterfelde. *Ornith. Monatsber.*, vol. 32, pp. 61-63.
1924b. *Puffinus griseus* (Gmelin) Brutvogel in der nordchilenischen Pampa. *Ibid.*, vol. 32, pp. 63-64.
1929. Eine weitere Fundstelle von *Oceanodroma hornbyi* in der chilenischen Salpeterwüste. *Ibid.*, vol. 37, p. 3.
- STRUNZ, H.
1939. Identität von Monit, Zeugit, Spodiosit und Apatit. *Naturwissenschaften*, vol. 27, p. 423.
- STUTZER, O.
1911. Die wichtigsten Lagerstätten der "Nicht-Erze." Berlin, Borntraeger.
- STUTZER, O., AND W. WETZEL
1932. *Phosphat-Nitrat*. [Second edition.] Berlin, Borntraeger, 390 pp.
- SVERDRUP, H. U.
1940. The gulf of California: Preliminary discussion of the cruise of the "E. W. Scripps" in February and March, 1939. *Proc. Sixth Pacific Sci. Congr. Pacific Sci. Assoc.*, vol. 3, pp. 161-166.
1944. The California current. In *Science in the University*, by members of the Faculties of the University of California. Berkeley and Los Angeles, University of California Press, pp. 97-111.
- SVERDRUP, H. U., M. W. JOHNSON, AND R. H. FLEMING
1942. The oceans, their physics, chemistry and general biology. New York, Prentice-Hall, Inc., 1087 pp.
- TANNER, J. A., JR.
1875. Analysis of crystallised ammonium oxalate from Guanapi guano. *Chem. News*, vol. 32, p. 162.
- TAYAMA, R.
1939. Terraces of the South Sea islands under the Japanese mandate. *Proc. Imp. Acad. Japan*, vol. 15, pp. 139-141.

- TAYLOR, G. C.**
1859. Account of a visit to a nesting-place of the frigate-bird (*Fregata aquila*, L.). *Ibis*, vol. 1, pp. 150-152.
- TAYLOR, T. GRIFFITH**
1920. *Australian meteorology*. Oxford, Clarendon Press, 312 pp.
- TAYLOR, W. J.**
1857. Investigation on the rock guano from the islands of the Caribbean Sea. *Proc. Acad. Nat. Sci. Philadelphia*, pp. 91-100.
1858. Mineralogical notes. *Ibid.*, pp. 172-176.
1859. Mineralogical notes, II. *Ibid.*, pp. 306-316.
- TEALE, E. O., AND F. OATES**
1934. The limestone caves and hot springs of the Songwe River (Mbeya) area with notes on the associated guano deposits. *Jour. East Africa and Uganda Nat. Hist. Soc.*, vol. 12, pp. 130-137.
- TEALL, J. J. H.**
1898. A phosphatized trachyte from Clipper-ton Atoll (northern Pacific). *Jour. Geol. Soc. London*, vol. 54, pp. 230-233.
- TEICHERT, C., AND R. W. FAIRBRIDGE**
1948. Some coral reefs of the Sahul Shelf. *Geogr. Rev.*, vol. 38, no. 2, pp. 222-249.
- TEMPANY, H. A.**
1915. Report on the island of Redonda. *West Indian Bull.*, vol. 15, pp. 22-26.
1928a. Phosphate on the island of Redonda. *Congr. Géol. internatl. Madrid (1926), Réserves Mondiales en Phosphates*, vol. 2, pp. 781-783.
1928b. *Mauritius. Ibid.*, vol. 2, p. 607.
- TESCHEMACHER, E. F.**
1846. An account of various substances found in the guano deposits and in their vicinity. *Phil. Mag.*, ser. 3, vol. 28, pp. 546-550.
- THIERRY, H.**
1874. Le guano du sud. In *Guanos de Tarapaca*, documents officiels, anglais et péruviens, publiés par la légation du Pérou en France. Paris, Librairie général, pp. 29-41.
- THOMPSON, E. F.**
1939. Chemical and physical investigations. The general hydrography of the Red Sea. John Murray Expedition, 1933-1934. London, printed by order of the trustees of the British Museum, vol. 2, no. 3, pp. 85-103.
- THOMPSTONE, E.**
1909. Bat's guano in Burma. *Agr. Jour. India*, vol. 4, pp. 379-381.
- THORADE, H.**
1909. Über die Kalifornische Meeresströmung. Oberflächentemperaturen und Strömungen an der Westküste Nordamerikas. *Ann. Hydrogr. Mar. Met.*, vol. 37, pp. 17-34, 63-76.
- TIETZE, E.**
1872. Ueber ein Vorkommen von Fledermausguano im Graner Gebirge. *Verhandl. k. k. geol. Reichsanst. Wien*, 1872, no. 12, pp. 247-249.
- TOD, W.**
1859. Die Landw. Versuchst., vol. 3, p. 264. Not seen; reference in *Jahresb. Agr. Chem.*, 1858-1861, Zweiter Jahrg., p. 231.
- TOKUNAGA, S.**
1940. A fossil elephant tooth discovered in Miyakozima, an island of the Ryûkyû Archipelago, Japan. *Proc. Imp. Acad. Japan*, vol. 16, pp. 122-124.
- TOWNSEND, C. H.**
1935. The distribution of certain whales as shown by logbook records of American whaleships. *Zoologica*, New York, vol. 19, pp. 1-50.
- TOWNSEND, C. H., AND A. WETMORE**
1919. Reports on the scientific results of the expedition to the tropical Pacific by the U. S. Fish Commission steamer "Albatross." XXI. The birds. *Bull. Mus. Comp. Zool.*, vol. 63, no. 4, pp. 149-225.
- TREMEARNE, T. H., AND K. D. JACOB**
1941. Arsenic in natural phosphates and phosphate fertilizers. *Tech. Bull. U. S. Dept. Agr.*, no. 781, 39 pp.
- TROMP, C. C.**
1880. *Tijdschr. voor Nijverheid en Landbouw. Ned. Ind.*, Batavia, vol. 25, p. 554. Not seen; reference in Wichman, 1915.
- TSCHUDI, J. J. VON**
1846. Peru. Reiseskizzen aus den Jahren 1838-1842. St. Gallen, Scheitlin and Zollikofer, 2 vols.
1851. Die Huanulager an der peruanischen Küste. *Denschr. K. Akad. Wiss. Wien, Math.-Nat. Classe*, vol. 2, pp. 1-20.
- TSENG, TA-BAO**
1946. Shin Nan Chung Dao Shih Wo Men Dee (New South Archipelago is ours). *Ta Kung Pao (L'Impartial)*, Shanghai, Aug. 4 and 5. [In Chinese.]
- TWELVETREES, W. H.**
1917. Phosphate deposits in Tasmania. *Geol. Surv. Mineral Resources, Dept. Mines, Tasmania*, no. 3, 9 pp.

- UÉNO, M.
1938. Plankton of the lakes in Kita-Daitô-Zima. Proc. Imp. Acad. Tokyo, vol. 14, pp. 16-17.
- ULBRICHT
[Analysis in Heiden, 1887.]
No reference; possibly private communication; no independent publication discovered.
- ULEX, G. L.
1848. Ueber natürliches zweifach-kohlensaures Ammoniak. Ann. Chem. Pharm., vol. 66, pp. 44-45.
- ULMANN, M.
1906. Die deutsche chemische Dünger-Industrie. Festschrift zum 25 jährigem Jubiläum der Begründung des Vereins Deutscher Dünger-Fabrikanten. Stralsund, W. Bergholz Nachf. (A. Steinthal) Buchhandlung.
- ULPIANI, C., AND M. CINGOLANI
1905. Sulla fermentazione della guanina. Atti R. Accad. Lincei, Cl. Sci. Fis., Mat. e Nat., vol. 14 (5), pt. 2, pp. 596-600.
- ULRICH, GEORGE H. F.
1870. Contributions to the mineralogy of Victoria. Melbourne, by authority John Ferrer, Government Printer, 32 pp.
- UNGER, BODO
1846a. Bemerkungen zu obiger Notiz [i.e., Einbrodt, 1846]. Ann. Chem. Pharm., vol. 58, pp. 18-20.
1846b. Das Guanin und seine Verbindungen. *Ibid.*, vol. 59, pp. 58-68.
- UNITED STATES COAST PILOT
1933. The Hawaiian Islands. Second edition. U. S. Dept. Commerce and U. S. Coast and Geodetic Survey, ser. no. 558, 128 pp.
- UNITED STATES GUANO COMPANY
1859. Report to the stockholders of the United States Guano Co. New York, 40 pp.
- UNITED STATES HYDROGRAPHIC OFFICE
1873. Hydrographic notice no. 45. U. S. hydrographic notices, from no. 1 to no. 97, for 1872. Washington, pp. 4-5.
1916a. South America pilot. Vol. III. West Coast from Corcovado Gulf to Panama including off-lying islands. Publ. no. 174, 510 pp.
1916b. Pacific islands pilot. Vol. II. Publ. no. 166, 480 pp.
1920a. Pacific islands pilot. Vol. I. Publ. no. 165, 693 pp.
1920b. Australia pilot. Vol. IV. North, north-west and west coasts between the western approach to Torres Strait and Cape Leeuwin. Publ. no. 170, 447 pp.
1920c. Mexico and Central America pilot (west coast). Publ. no. 84, 423 pp.
1922. West Indies pilot. Vol. I. Publ. no. 128, 657 pp.
1924. East Indies pilot. Vol. I. Publ. no. 163, 608 pp.
1926. Pacific islands pilot. Vol. II (Eastern groups). Publ. no. 166, 619 pp.
1927a. West Indies pilot. Vol. I. Publ. no. 128, 706 pp.
1927b. South Indian Ocean pilot. Publ. no. 161, 546 pp.
1927c. Central America and Mexico pilot (east coast). Publ. no. 130, 424 pp.
1927d. South America pilot. Vol. I. Publ. no. 172, 550 pp.
1928a. Mexico and Central America pilot (west coast). Publ. no. 84, 446 pp.
1928b. Pacific Islands pilot. Vol. I. Publ. no. 165, 788 pp.
1929a. West Indies pilot. Vol. II. The Lesser Antilles and the coast of Venezuela. Publ. no. 129, 471 pp.
1929b. New Zealand pilot. Publ. no. 171, 528 pp.
1930a. Asiatic pilot. Vol. II. Publ. no. 123, 862 pp.
1930b. Australia pilot. Vol. I. Publ. no. 167, 372 pp.
1930c. Australia pilot. Vol. III. Publ. no. 169, 628 pp.
1931. Sailing directions for Australia. Vol. II. Publ. no. 168, 522 pp.
1932a. Sailing directions for the southwest coast of Africa. Publ. no. 105, 442 pp.
1932b. Sailing directions for Australia. Vol. IV. Publ. no. 170, 494 pp.
1935. Sailing directions for South America. Vol. I. Publ. no. 172, 464 pp.
1936a. Sailing directions for the southeast coast of Africa. Publ. no. 156, 455 pp.
1936b. Sailing directions for New Guinea and the islands eastward of Celebes and Timor. Publ. no. 164, 651 pp.
1937a. Sailing directions for the western shores of the China Sea. Publ. no. 125, 484 pp.
1937b. Sailing directions for the West Indies. Vol. II. Publ. no. 129, 416 pp.
1937c. Bulletin, July 14, 1937.
Not seen; reference in Bryan, E. H., Jr., 1939a.
1939. Sailing directions for east coasts of central America and Mexico. Publ. no. 130, 382 pp.
1940. Sailing directions for the Pacific islands. Vol. II. Publ. no. 166, 522 pp.
1943. Sailing directions for the Red Sea and the Gulf of Aden. Publ. no. 157, 549 pp.

URETA Y PERALTA, PEDRO DE

1792a. Descripción de la Ciudad de Arica, y su Vasta jurisdicción correspondiente á la Intendencia de Arequipa en el Peru. *Mercurio Peruano*, vol. 6, pp. 114-144. Guano, pp. 118-119.

1792b. Manifestación de la Pureza de Voces y conceptos de la Descripción de Arica y su Provincia contra la dudas y reparos del IGNORANTE, contenidos en el *Mercurio* numero 193. *Ibid.*, no. 199, pp. 213, 238.

URTEAGA, HORACIO H., AND DOMINGO ANGULO

1940. Autos que se comenzaron por mandado del excmo. Señor Duque de la Palata, Virrey de Estos Reyno, para trasladar la Villa de Pisco a no paraxe mas seguro y alexado de la Mar.—Año de 1688—[cont.] Petición [signed by "el Bachiller Gabriel de Siles," and numerous other persons]. *Rev. Arch. Nac. Peru*, vol. 13, pp. 169-173.

VÁZQUEZ DE ESPINOSA, ANTONIO

1942. Compendium and description of the West Indies. Translated by Charles U. Clark. *Smithsonian Misc. Coll.*, vol. 102 (whole vol.), 862 pp.

VAUGHN, T. W.

1901. Some fossil corals from the elevated reefs of Curaçao, Aruba and Bonaire. *Samml. Geol. Reichsmus. Beitr. Geol. Palaeont. Niederl. Indien* (II), vol. 2, pp. 1-91.

1919. Fossil corals from Central America, Cuba and Porto Rico. *Bull. U. S. Natl. Mus.*, no. 103, pt. 9, pp. 189-524.

VAUQUELIN, L. N.

1822. Analyse d'un phosphate d'alumine naturel. *Ann. Chim. Phys.*, vol. 21, pp. 188-196.

VERNADSKY, W. I.

1938. On the terrestrial alumophosphorus and alumosulphurous analogues of kaolinic alumosilicates. *Compt. Rendus (Doklady)*, Acad. Sci. URSS, vol. 18, pp. 287-294.

VESEY-FITZGERALD, D.

1941. Further contributions to the ornithology of the Seychelles Islands. *Ibis*, ser. 14, vol. 5, pp. 518-531.

1942. Further studies of the vegetation on islands in the Indian Ocean. *Jour. Ecol.*, vol. 30, pp. 1-16.

VIDAL GORMAZ, F.

1880. Estudio sobre El Puerto de Iquique. Chile, Imprenta nacional, 24 pp.

VILLANUEVA, A.

1878. Guanos i salitres del desierto de Ata-

cama. *An. Univ. Chile*, vol. 53, pp. 403-443.

VINOGRADOV, A. P.

1944. La composition chimique elementaire des organismes marins. Part III. *Trav. du Lab. Biogéochim. Acad. Sci. de l'URSS*, vol. 6, pp. 1-273.

The entire work, of which this is the third part, will appear in English translation as *Memoir Sears Foundation for Marine Research*, no. 2.

VOELCKER, A.

1860. On the chemical composition and commercial value of Norwegian apatite, Spanish phosphorite, coprolites, and other phosphatic materials used in England for agricultural purposes. *Jour. Roy. Agr. Soc.*, ser. 1, vol. 21, pp. 350-381.

1864. Professor Voelcker's annual report. 3. Analysis of Egyptian guano. *Ibid.*, ser. 1, vol. 25, pp. 236-238.

1872. Report of the consulting chemist for 1871. *Ibid.*, ser. 2, vol. 8, pp. 215-226.

1874. Report on the composition of thirteen samples of Peruvian guano, sent by the secretary of the Admiralty to the Royal Agricultural Society of England. *Ibid.*, ser. 2, vol. 10, pp. 541-546.

1875. On the chemical composition of phosphatic minerals used for agricultural purposes. *Ibid.*, ser. 2, vol. 11, pp. 399-435.

1876. On phosphatic guanos. *Ibid.*, ser. 2, vol. 12, pp. 440-459.

1877. Annual report of the consulting chemist for 1876. *Ibid.*, ser. 2, vol. 13, pp. 188-200.

1878a. On bat's guano. *Ibid.*, ser. 2, vol. 14, pp. 60-72.

1878b. Annual report of the consulting chemist for 1877. *Ibid.*, ser. 2, vol. 14, pp. 246-255.

VOELTZKOW, A.

1897. *Wissenschaftliche Ergebnisse der Reisen in Madagaskar und Ostafrika in den Jahren 1889-1895. Abhandl. Senckenbergische Naturfor. Gesellsch.*, vol. 21, pp. 1-76.

VOGT, W.

1940. Una depresión ecológica en la costa peruana. *Bol. Compañía Administradora Guano, Lima*, vol. 16, no. 10 (conferencias), pp. 307-329.

1941. Informe anual. *Ibid.*, vol. 17, pp. 127-168.

1942. Informe sobre las aves guaneras elevado

- a la Compañía Administradora del Guano. *Ibid.*, vol. 18, no. 3, pp. 3-132.
1946. Report of an airplane inspection trip made over the islands in the Gulf of California and off the Pacific coast of lower California. In Report on Activities of the Conservation Section, Division of Agricultural Cooperation, Pan American Union (1943-1946). Washington, D. C., Pan American Union, app. 4, pp. 112-119.
- VOIGT, F.
1875. [Analysis.]
In Heiden, 1887, p. 440.
- VOLTERRA, V.
1926. Variazione e fluttuazioni del numero d'individui in specie animali conviventi. Mem. R. Accad. Naz. Lincei, ser. 6, vol. 2.
- WAITE, EDGAR R.
1909. Vertebrata of the Subantarctic Islands of New Zealand. In Chilton, C., The Subantarctic Islands of New Zealand, vol. 2, art. 25, pp. 542-600. New Zealand, The Philosophical Institute of Canterbury, vol. 2, art. 25, pp. 542-600.
- WALCOTT, F. C.
1925. An expedition to the Laguna Colorada, southern Bolivia, with a note on the recent occurrence of "El Nino." Geogr. Rev., vol. 15, pp. 345-366.
- WALDIE, DAVID
1845. Guano: its composition, analysis, and valuation and an exposure of malpractices connected with guano sales in Liverpool. London, James Gilbert; Liverpool, George Philip, 28 pp.
Pamphlet.
- WALKER, CAPT. F. D.
1909. Log of the Kaolokai, being a description of small islands, shoals and reefs lying WNW of the Hawaiian group proper. Honolulu, 64 pp.
- WALKER, J.
1892. The bird-life of Adèle Island, northwest Australia. Ibis, ser. 6, vol. 4, pp. 254-261.
- WALSH, T. CROSBIE
1930a. The gannets of White Island. Wanderlust Mag., Auckland, New Zealand, vol. 1, pp. 1-14.
1930b. White Island. *Ibid.*, vol. 1, pp. 47-60.
- WARD, HENRY L.
1904. A study in the variations of proportions in bats, with brief notes on some of the species mentioned. Trans. Wisconsin Acad. Sci., Arts, Letters, vol. 14, pt. 2, pp. 630-654.
- WARD, L. KEITH
1928. The phosphate resources of south Australia. Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates, vol. 2, pp. 811-813.
- WARINGTON, R.
1845. On a curious change in the composition of bones taken from the guano. Mem. Proc. Chem. Soc. London, vol. 2, pp. 223-226.
- WASHINGTON, H. S.
1929. Dahllite from St. Paul's Rocks (Atlantic). Amer. Min., vol. 14, pp. 369-372.
- WATERTON, CHARLES
1839. Wandering in South America, the northwest of the United States and the Antilles in the years 1812, 1816, 1820 and 1824. London, J. Mauman.
- WATSON, A. C.
1930. The guano islands of southwestern Africa. Geogr. Rev., vol. 20, pp. 631-641.
- WAY, J. THOMAS
1849. On the composition and money value of the different varieties of guano. Jour. Roy. Agr. Soc., ser. 11, vol. 10, pp. 196-230.
- WEBB, W. H., AND J. B. SARDY
1859. Guano as a fertilizer. New York, Slote and Janes, 20 pp.
Trade pamphlet.
- WEBER, M. W.
1902. Introduction et description de l'expédition. *Monograph 1 in* Uitkomsten op Zoologisch, Botanisch, Oceanographisch en Geologisch Gebied verzameld in Nederlandsch Oost-Indie 1899-1900. Siboga Expedition. Leiden, E. S. Brill.
- WEIGELT, C.
1880. Fledermaus Guano. Deutsche Landw. Zeitg., vol. 5.
Not seen; reference in Sestini, 1895.
- WENTWORTH, C. K.
1931. Geology of the Pacific equatorial islands. Occas. Papers Bernice P. Bishop Mus., vol. 8, no. 15, 25 pp.
- WENTWORTH, C. K., AND H. S. PALMER
1925. Eustatic bench of islands of the north Pacific. Bull. Geol. Soc. Amer., vol. 36, pp. 521-544.
- WESTERMANN, J. H.
1931. Aruba. Leidsche Geol. Meded., vol. 5, pp. 709-714.
1932. The geology of Aruba. Utrecht, A. Oosthoek's Uitgevers-Mootij, 129 pp.
Thesis.
- WETMORE, A.
1918. The birds of Desecheo Island, Porto Rico. Auk, vol. 35, pp. 333-340.

1924. A warbler from Nihoa. *Condor*, vol. 26, pp. 177-178.
- 1925a. The Coues gadwall extinct. *Ibid.*, vol. 27, p. 36.
- 1925b. Bird life among lava rock and coral sand: The chronicle of a scientific expedition to little-known islands of Hawaii. *Natl. Geogr. Mag.*, vol. 48, pp. 77-108.
1927. The birds of Porto Rico and the Virgin Islands. *New York Acad. Sci., Sci. Surv. Porto Rico and the Virgin Islands*, vol. 9, pts. 3 and 4, pp. 243-598.
1939. Birds from Clipperton Island collected on the Presidential cruise of 1938. *Smithsonian Misc. Coll.*, vol. 98, 6 pp.
1945. A review of the forms of the brown pelican. *Auk*, vol. 62, pp. 577-586.
- WETMORE, A., AND B. H. SWALES
1931. The birds of Haiti and the Dominican Republic. *Bull. U. S. Natl. Mus.*, no. 155, 483 pp.
- WETTSTEIN-WESTERSHEIM, O.
1931. Die diluvialen Kleinsäugerreste. In Abel, O., and G. Kyrle, *Die Drachenhöhle bei Mixnitz*. Vienna, (Verlag) Österr. Staatsdruckerei, Spelaol. Monogr., vols. 7, 8, pp. 769-789.
- WETZEL, W.
1925. Vogelmumien und "Guano" in chilenischen Salpeter-Ablagerungen. *Zentralbl. Min., Geol., Paleont., ser. A*, 1925, pp. 284-288.
1930. Der Wüstenguano der hochariden Zone Nordchiles. *Chemie der Erde*, vol. 5, pp. 260-275.
- WHARTON, ADMIRAL SIR W. J.
1898. Note on Clipperton Atoll (northern Pacific). *Quart. Jour. Geol. Soc. London*, vol. 54, pp. 228-229.
- WHEELER, J. F. G.
1945. Plant nutrients in the sea. *Nature*, vol. 155, pp. 731-732.
- WHEELER, WILLIAM MORTON
1928. The social insects, their origin and evolution. London, K. Paul, Trench, Trubner and Co.; New York, Harcourt, Brace and Co., 378 pp.
- WIBEL, F.
1874. Ueber Guanovulit, ein neues Mineral in den Vogeleiern des Peru—Guanos. *Ber. Deutsche Chem. Gesellsch.*, vol. 7, pp. 392-396.
- WICHMANN, A.
1915. On phosphorite of the isle of Ajawi. *K. Akad. Wetensch., Amsterdam, Proc. Sect. Sci.*, vol. 18, pt. 1, pp. 214-220.
1933. Informes sobre depósitos de guano en dos islas de la costa Atlantica. II. La isla Penguin y sus depósitos de guano (Temtona de Santa Cruz). *Argentina Direc. Minas y Geol., publ. 100*, pp. 21-23.
- WICKE, WILHELM
1859. [Analysis of Sombrero phosphate.] *Jour. für Landw.*, 1859, p. 268.
Original not seen; abstract in *Jahresber. Agr. Chemie*, 1861, vol. 2, p. 232.
- WILDER, G. P.
1934. The flora of Makatea. *Bull. Bernice P. Bishop Mus.*, vol. 120, 49 pp.
- WILKE-DÖRFURT, E., J. BECK, AND G. PLEPP
1928. Über das Vorkommen von Jod in Phosphatlageren. *Zeitschr. Anorg. Allg. Chem.*, vol. 172, pp. 344-352.
- WILKES, C.
1845. Narrative of the United States' exploring expedition... during the years 1838-1842. Philadelphia, Lea and Blanchard, vol. 3.
- WILKINS, G. H.
1923. Report on the birds collected during the voyage of the "Quest" (Shackleton-Rowett expedition to the southern Atlantic). *Ibis*, vol. 5, pp. 474-511.
- WILLIAMS, C. P.
1871. On the solubility of some forms of phosphate of lime. *Chem. News*, vol. 24, p. 306.
- WILLIMZIK, M.
1929. Die Strömungen im subtropischen Konvergenzgebiet des Indischen Ozeans. *Veröffentl. Inst. für Meereskunde, Univ. Berlin*, new ser. A, geogr.-naturwiss. ser., vol. 14, pp. 1-27.
- WILLIS, B., AND H. S. WASHINGTON
1924. San Felix and San Ambrosio: their geology and petrology. *Bull. Geol. Soc. Amer.*, vol. 35, pp. 365-384.
- WIMPFEN, FRANÇOIS ALEXANDRE STANISLAUS, BARON DE
1817. A voyage to Saint Domingo in the years 1788, 1789 and 1790. Translated from the original manuscript which has never been published, by J. Wright. London, T. Cadell, junior, and W. Davies, 371 pp.
- WINGE, HERLUF
1893. Jordfundne og nulevende Flagermus (Chiroptera) fra Lagoa Santa, Minas Geraes, Brasilien. *E Museo Lundii. En Samling af Afhandlinger om de i det Brasiliens Kalkstenshuler af Professor Dr. Peter Vilhelm Lund*, vol. 2, pt. 1, art. 1, 92 pp.

- WODZICKI, K. A., AND C. P. McMEEKAN
1947. The gannet on Cape Kidnappers. Trans. Roy. Soc. New Zealand, vol. 76, pp. 429-452.
- W[OHLER, FRIEDRICH]
1841. Ueber die Zusammensetzung des Guano. Ann. Chem. Pharm., vol. 37, pp. 285-292.
- WOLF, BENNO
1934-1935. Catalogus animalium cavernarum. The Hague, W. Junk, vol. 1, Praefatio, introductio, bibliographia, xxiii + 108 pp.; vol. 2, Cavernarum catalogus, 616 pp.; vol. 3. Animalium catalogus, 918 pp.
- WONG, W. H., AND C. Y. HSIEH
1928. Phosphate deposits of China. Congr. Géol. internatl. Madrid, Réserves Mondiales en Phosphates, vol. 2, p. 547.
- WOOD AND GRANT
1857. Phosphatic guano from Sombrero Island, West Indies. New York, 16 pp. Trade pamphlet.
- WOODWARD, H. P.
1912. Guano deposits at Watheroo, West Australia. Geol. Surv. Bull., no. 48, misc. rept. 10, pp. 22-29.
- WRIGHT, H. W.
1913. The birds of San Martin Island, Lower California. Condor, vol. 15, pp. 207-210.
- WYNDHAM, C.
1932. Pelicans breeding on Seal Island. Ostrich, vol. 3, pp. 1-5.
- YABE, H., AND T. SUGIYAMA
1934. Subfossil gizzard stones probably of birds found in the phosphate deposit of Kita-Daitô-Zima. Proc. Imp. Acad. Japan, vol. 10, pp. 361-364.
1935. Notes on a fossil shark's tooth found in the Daitô limestone of Kita-Daitô-Zima, Borodino Islands. *Ibid.*, vol. 11, pp. 149-151.
- YAMANARI, HUZIMA
1935. Aluminum phosphate deposit in Kita-Daitô-Zima. [In Japanese.] Tôhoku Imp. Univ. Res. Contrib. Inst. Palaeont., no. 15, 65 pp.
- YOSHIWARA, S.
1901a. Notes on the raised coral reefs in the islands of the Riukiu curve. Jour. College Sci., Imp. Univ. Tokyo, vol. 16, art. 1, 14 pp.
1901b. Geologic structure of the Riukiu (Loochoo) curve, and its relation to the northern part of Formosa. *Ibid.*, vol. 16, art. 2, 67 pp.
- YOSHIMURA, S.
1938. Limnology of two lakes on the oceanic island, Kita-Daitô-Zima. Proc. Imp. Acad. Tokyo, vol. 14, pp. 12-15.
- ZAMBONINI, F.
1907. Zeitschr. Krist., vol. 42, p. 87 (1906). *Abstract of* Casoria, E., Über ein neues wasserhaltiges Aluminium-kaliumphosphat, Annali R. Scuola Sup. di Agricoltura di Portici, 1904.
- ZEEDERBERG, W. R.
1915-1916. Government Guano Islands. (Annual report of the Superintendent.). U. G. 25, '17, pp. 131-135.
1916-1917. Government Guano Islands. (Annual report of the Superintendent.). U. G. 5, '18, pp. 143-147.
1918. Government Guano Islands. U. G. 39, '18, pp. 149-153.
1919. Government Guano Islands. U. G. 40, '19, pp. 145-150.
1921. Government Guano Islands. U. G. 13, '21, pp. 71-74.
1926. A valuable asset to the farmer (Guano and other island products). Farming in South Africa, p. 330.
1927. *Ibid.*, p. 454.
1928. *Ibid.*, p. 1133.
- ZEUNER, FRIEDRICH E.
1945. The Pleistocene period, its climate, chronology and faunal successions. London, printed for the Ray Society, sold by B. Quaritch, Ltd., 322 pp.
- ZIES, E. G.
1929. The valley of Ten Thousand Smokes. Natl. Geogr. Soc. Contributed Technical Papers, Katmai Series, vol. 1, no. 4, pp. 1-79.
- ZIMMERMAN, ELWOOD C.
1936. A cryptorrhynchid from Marotiri (Coleoptera, Curculionidae). Occas. Papers Bernice P. Bishop Mus., vol. 12, no. 21, 4 pp.
1948. Insects of Hawaii. Honolulu, University of Hawaii Press, vol. 1, 206 pp.
- ZIRAVELLO, A.
1892-1893. Annuario R. Scuola Enol. Cagliari, vol. 2, p. 46.
Not seen; reference in Binaghi, 1909.
- ZÚÑIGA, ALBERTO GONZÁLEZ
1944. Lobos marinos. Fuente de riqueza. Bol. Compañía Administradora Guano, Lima, vol. 20, pp. 119-135.

INDEX

- Abd-el-Kuri, 304, 305
 Abrolhos Islands, 352
Acervulina inhaerens, 238
 acetic acid, 77
Acrocephalus lusciniæ rehsei, 214
 actinolite, 275, 478
 Adelaide Island, 122
 Adelaide, South Australia, 274
 Adelaide River, 274
 Adèle Island, 270, 272
 Aden, 305
 Aden Crater, New Mexico, 398
 Admiralty Islands, 223
 Africa, cave guano, 418 *et seq.*
 Africa, South West, 134–157
 African Banks, Seychelles, 290, 291
 African Islands, Amirante Islands, 295
 Agalega Islands, 294, 302
 Agiguwan Island, 235
 Agua Fria, Texas, 397
 Agua Verde, 112
 Aguadilla, 385, 387
 aguaje, 10, 11, 52, 53, 137, 139
 Aguas Blancas, 112, 113
 Aguas Buenas, Puerto Rico, 385
 Aguijan, 235, 251, 252, 376–378
 Agulhas Current, 136, 151
 Aguni Shima, 248
 Ain, 444
 Aïn Bessem, 422
 Aïn-Fezza, 422
 Ait Zikki, 422
 Ajawi, 226, 227, 303, 376, 469
 Ajax Mine, 274
 Aka-ike Lake, Kita Daito Jima, 237
 Akaroa, 410
 Alabama, 394, 402
 Alacrán Island, 46, 48, 53, 318
 Alacran Rocks, Caribbean Sea, 323
 Alacranes Cay, 323
 Alba, Rumania, 428
 albatross, Laysan, 186
 Albatross Island, 28
 Albatross Rock, Hollam's Bird Island, 146
 Albatross Rock, Hunter group, 265
 albatrosses, 5, 62, 166, 200–202, 207, 237, 239, 263, 264, 314
 album graecum, 458
 alcatraz, 20
 Alcatraz Island, 158, 367
 Alcatrazes Islands, 353
 Alcidae, 366
 Aldabra Island, 215, 217, 288, 290–294, 296–299, 303, 323, 376–378, 469, 482
 Aleutian Current, 122
 Alexander Bay, 136
Alexia, 420
 algae, 61, 125, 174, 220, 262, 273, 326
 Algeria, 422, 424, 466, 467, 479
 Alghero, 453
 Algoa Bay, 134, 140, 151, 153
 Alicante, 451, 452
 Alim Island, 226
 alkaline salts in guano, 85
 allantoin, 72, 77
 Allègre, 446
 Allison Island, 226
 allophane, 350
Alopecurus alpinus, 370
 Alpes Maritimes, 444
 Alphonse Island, 288, 295, 296, 302
 Alpine, Texas, 397
 Alpine Massif, 444
 Alps, 445
 See also Alpes Maritimes, Alpine Massif, Basses
 Alpes, French Alps
 Alsace Lorraine, 446
 Alta Vela, 322, 325, 344, 345, 362, 376, 475, 476, table 54
 Altamura Island, 124
 Althorpe Islands, 267
 aluminum, 192, *passim*
 aluminum ferric phosphates, 73, *passim*
 aluminum oxide, 156, *passim*
 Amazon, 345
 Amboarana, 421
 Amboina Cay, 276, 284
 Amboni, 420
 America Island, 188
 American River, Australia, 267
 Amirante Islands, 288, 290, 291, 294, 295, 302, 368
 ammonia, 27, 77, *passim*
 ammonium bicarbonate, 40, 77, *passim*
 ammonium carbonate, 78, *passim*
 ammonium chloride, 93, *passim*
 ammonium citrate, 288, *passim*
 ammonium oxalate, 77, *passim*
 ammonium phosphate, 75, 92, *passim*
 ammonium silicate, 192
 Ampalasa, 285
 amphipod, 420
Amphisbaena ridleyi, 347
Amphistegina radiata, 238
 Amphitrite group, Paracel Reefs, 279
 Ampombimarivola, 421
 anaerobes, 77
Anas platyrhynchos laysanensis, 201
 streperus couesi, 167, 375
 Anchor Key, Serrana Cays, 321
 anchoveta, 14, 15, 18, 19, 21, 53, 54, 58

- Anchovia macrolepidota*, 124
Anchoviella compressa, 124
 delicatissima, 124
 hellert, 124
 Ancon, 21, 32, 43
 Ancones, 387, 388, 480
 Ancora Islands, 352
 andesite, 122, 234, 328, 329, 476, table 54
 Andramahiba Bay, 299
 Angamos, 78
 Angamos Point, 47, 72, 73, 75, 114, 115
 Angaur, 299–322, 251, 252, 340, 363, 364, 376–378, 471
 Angel de la Guarda Island, 124, 130
 Angola, 134
 Angra Pequena Bay, 142, 146, 147, 151
 See also Luderitz Bay
 Anguilla, 328, 331
Anhinga, 60
 Animas, 44, 98
 Animas Valley, New Mexico, 399
Anina lacustris, 420
 Ankoriko Peninsula, 421
 Annam, 413
 Anne Island, 188
Anous, 186, 214, 293
 leucocapillus, 212, 291
 minutus, 187, 210, 212, 213, 347
 minutus atlanticus, 311, 346
 minutus diamesus, 197
 minutus marcusii, 236
 minutus melanogenys, 165, 201, 202, 206, 207
 stolidus hawaiiensis, 210
 stolidus, 120, 206, 207, 210, 236, 256, 286, 313, 333, 347, 370
 stolidus gilberti, 270, 273
 stolidus pileatus, 165, 201, 202, 205, 255, 291, 372
 stolidus plumbeigularis, 305, 367
 stolidus ridgwayi, 197
 stolidus stolidus, 311, 318, 326, 327, 346
 tenuirostris, 273
 tenuirostris tenuirostris, 290, 291, 293, 294
 Antarctic Ocean, 380
 antelopes, 418
Anthus steindachneri, 263, 369
 Antigua, 332
 Antipodes Island, 260, 263, 369, 370
 Antofagasta, 48, 112
Antroscelio lucifugax, 420
Antrozous pallidus, 395
 ants, 4
 Apaiang, 213
 Apatahi, 212
 apatites, 3, 118, 198, 204, 206, 221, 306, 313, 331, 343, 344, 347, 449, 465, 467–470, 473, 474, 477, 482
 apththalite, 91
 Apia, Tahiti, 188
 Apia Island, 213
Apodemus sylvaticus, 433
 Arabia, 308
 Arabian Sea, 288
 Aragon River, 451
 aragonite, 220, 339
 Araure, 382
 Arborath, 411
 arcanite, 91, 463
 archaeological finds, beneath guano, 30
 Csoklovina Cave, 428
 Fanning Island, 184
 Las Vegas, Nevada, 401, 402
 Macabí, 29
 Malden Island, 175, 193
 Washington Island, 194
 See also artifacts
 Arctic Ocean, 361
Arctocephalus forsteri, 262
 ardealite, 429, 465
 Ardèche, 444, 445
 Arecibo, 385, 387
 Arequipa, 45
 Argyllshire, 457
 Aricá, 23, 43–47, 50, 51, 53, 86, 98
 Ariège, 445, 447
 Arizona, 401
 Arkansas, 394, 405
 Arkhangel Bay, 369, 370
 arsenic, 340, 348, 474
 arthropodin, 381, 460, 462
 arthropods, 113
 Arthurs Island, 179, 189
Artibeus, 381, 389
 jamaicensis jamaicensis, 385, 389, 391
 jamaicensis parvipes, 389
 artifacts, 66, 67, 69, 411
 Drachenhöhle, 433
 Middle Stone Age, 157
 paleolithic, 157
 Stellenbosch, 157
 Aruba, 318, 333, 341, 342, 345, 376, 378
 Arumenii, 228
 Arzberghöhle, 438
 Ascension Island, 311–313, 367, 368, 465, 474
 Ascension Island frigate bird, 311
 Ashburnham, New South Wales, 409
 Ashmore Shoals, 271, 285
 Asia Islands, 18, 21–23, 32, 48, 52, 55, 56, 73, 75, 76
 aspergillosis, 19
Aspergillus fumigatus, 19, 53
Asplenium nidus, 184
 Assumption Island, 288, 291–293, 297, 299, 302, 303
 Astove Island, 288, 292, 296, 299, 302
 Asunción Island, 128, 129
 Atacama Desert, 96, 112, 133

- Atafu, 190
Atherinopsis californicus, 127
 Atjen, 413
 Atlantic Ocean, 5, *passim*
 Attie, 417
 Aua Island, 226
 Aude, 445, 447
 augite, 476, table 54
 Austral Islands, 167, 175, 184
 Australasia, 253 *et seq.*
 Australia, 253, 362, 363, 365, 409, 477
 Australian gannet, 266
 pelican, 255
 Austria, 381, 424, 431, 439, 440
 Ava, 374
 Avalo Island, 322
 Ave de Barlovento, 317, 335, 336, 345, 367
 Ave de Sotavento, 335, 336, 345
 Aventignan, 424
 Aves Islands, 331, 332, 335, 336, 345, 464
 Aveyron, 444
 Azerou bou Adhfel, 422
 Azores, 158

 Baar's Island, 285
 Babel Islands, 266
Bacilli, 78
Bacillus fastidiosum, 76
 fluorescens non-liquifaciens, 77
 guano, 78
 pyocyaneus, 77
 Bacon Island, Fiji group, 187
 bacteria, 77, 89, 176, 402, 461, 463
Bacterium calco-aceticum, 77
 Bacunagua, 390
 Baden, 439
 badger, 438, 457
 Badlgraben, 437
 Badlhöhle, 437, 438
 Bärenhöhle, 438
 Bärenhorst, 441
 Bahama Islands, 322, 344, 391–393
 Bahia, 382
 Bahia Honda, 390
 Bahrein Islands, 310
 Baja California
 See Lower California
 Bajo Nuevo, 320, 321
 Baker Island, 153, 163–165, 167, 168, 170–172,
 174, 176, 181, 186, 193, 194, 250, 364, 374,
 379, 465, 469, 474
Balaena australis, 260
 Balaguer, 452
Balanus, 33
 Balearic Islands, 452
 Balkans, 424, 427
 Ballarat, 406

 Ballestas Islands, 18, 22, 23, 43, 44, 48, 51, 52, 59,
 62, 63, 66, 67, 73, 81–83, 87
 Bampton Island, 258
 Banaba Island, 214
 bananas, 235
 Bandera County, Texas, 395
 Bandon Rock, 267
 Bandurrias, 113, 115
 Banrock County, Idaho, 402
 Baoumo de la Campana, 447
 Baoussé-Roussé, 458
 Barbados, 317
Barbastella barbastella, 433
 schadleri, 424, 433, 434
 barbastelle, 433
 Barber Island, 189
 Barbuda, 326
 Barcelona, 451
 Bar-hink, 413
 barium, 468
 Barjac, 446
 Barlovento, Pabellón de Pica, 102, 108
 barrandite, 155, 156, 159, 275, 287, 306, 328, 337,
 378, 421, 473, 475–478, 480
 Barrenc de Prapérié, 445
 Barrington Island, 29, 121
 Barrio Ancones, 387
 Barrio Monte Grande, 386
 basalt, 33, 203, 205, 229, 248, 313–315, 328, 397,
 421, 422, 474, table 54
 Basra, 310
 Bass Rocks, 188
 Bass Strait, 253, 264–266, 366
 Basses Alpes, 444
 Basses Pyrénées, 445, 447
 Bassin Bleu, 421
 Bassin de la Plaine des Cabris, Aldabra, 299
 Bassin du Cormoran, 421
 bat, Mexican free-tailed, 393
 Batangas, 413
 bats (and bat guano), 3, 5, 153, 326, 327, 381–389,
 391–398, 401–406, 408–413, 415, 416, 418–
 429, 433, 434, 438, 439, 441–447, 450–453,
 455–459, 461–464, 467, 479, 480, 482
 fish-eating, 381, 385, 393
 free-tailed, 393, 424
 fruit-eating, 381, 385, 387
 horseshoe, 423
 insectivorous, 381, 385, 389, 391, 394
 vampire, 395
 vespertilionid, 423, 424
 Batu Caves, 415
 Batu Kapal, 284
 Batu Kurau, 415
 Bauladu, 456
 Bauman Island, 189, 190
 Baume des Italiens, 446
 Baume Sourde, 447

- Baume-les-Messieurs, 447
bauxite, 348, 349
Bavaria, 444
Bay of Barassoli, 307
Bay of Diego-Suarez, 421
Bay of Ferrol, 31
Bay of Guaymas, 124
Bay of Mejillones, 113
Bay of Pisco
 See Pisco Bay
Bay of Plenty, 261
Bay of San Cristobal, 128
Bay of Santa Inez, 334
Bayovar, 22, 26
Beacon Cay, Serranilla Cays, 321
Beagle Island, 270, 272
Beagle Islets, 272
bean, 272
bears, 381, 396, 423, 428, 433, 437, 438, 441-443, 457
Beata Island, 325
Beatrice Island, 267
Beduer, 425, 449, 450
beetles, 112, 394, 420
 cicindelid, 197
Beius, 428
Bellenden-Ker Mountains, 253
Beltana, 274
Benabarre, 451
Bendithera, 409
beneditos, 352
Benguela Current, 136, 137
Beni Mendes, 422
Benkoelen, 413
Benoea Ampat, 412
beraunite, 275
Berbera, 303, 305, 306
Berkeley Sound, 358
Bermeja Island, 26-28
Berrueco, 452
Besançon Sud, 446
bicarbonate, 464
Bickers Islets, 267, 268
Biert, 445
Big Bone Cave, Tennessee, 404
Bihor, 427, 428
Bikar Atoll, 228, 250, 251, 373, 374
Bikini Atoll, 365
biotite-granite, 269
biphosphammite, 92
bird, white, 314
Bird Island, Algoa Bay, 134, 136, 140, 144, 151-153
Bird Island, Caribbean Sea, 328, 331, 332, 344, 345, 362, 371
Bird Island, Nihoa, Hawaiian Leewards, 202
Bird Island, Seychelles, 288, 290-292, 294, 299, 302, 303
Bird Island, western Pacific, 235
Bird Islands, Cargados Carajos, 293
Bird Islet, Fanning Island, 185
Bird Islet, Palmyra Island, 165
Bird Islet, Wreck Reef, off Australia, 257
Bird Rock, Gulf of California, 128, 129
Bird Rock, Walvis Bay, 134
birds, 4, *passim*
Bird's Island, south Pacific, 257
Birnie Island, 177, 178
Bishops Hole, 410
Black Cavern, Borneo, 411
Black Hawk Island, 271
black-bird, 314
Blaine County, Idaho, 402
Blanca Island, 15, 44, 51, 54
Blanco County, Texas, 395, 396
Blanco Islet, Caribbean, 333, 345
Blanquilla, 333
blue herons, 290
Blyth Island, 267
Boatswain Bird Island, 311, 312, 367
boatswain's bird, red-tailed, 186
Bob Island, 147
bobierrite, 119, 408, 474, 482
Bocca Oliva, 338
Bodega de Zaragoza, 391
Boerhaavia, 168, 179, 371
 diffusa, 168, 186, 204
 tetrandra, 168, 170, 172
Bohol, 412, 414
Bokoloso, 421
Boljevac, 426
Bonaire, 318, 333, 337, 338, 345, 376, 378
Bonansa, 451
Bone Cave, New South Wales, 409
Bonin group, 236
bonitos, 18, 19
Booby Hill, St. Paul's Rocks, 346
Booby Island, Indian Ocean, 293
Booby Island, Queensland, 321
Booby Key, Serrana Cays, 321
boobies, 5, 20, 29, 120, 121, 125, 126, 131, 165, 166, 169, 181, 183, 187, 191, 192, 197, 202, 203, 248, 255, 256, 284, 291, 296, 305, 307, 311, 313, 314, 317, 318, 327, 332, 346, 347, 367, 368, 371
 blue-faced, 291
 Brewster's, 132, 367
 brown, 133, 186, 196, 236, 291, 318, 326
 masked, 186, 305
 red-footed, 168, 292
 yellow-footed, 335
Boone County, Missouri, 402
Borenore Caves, 409
Borneo, 276, 278, 410-412
Borodino group, 223, 236
Boromys torrei, 389

- boron, 86, *passim*
 borophosphate, 116
 Bosa, 453
 Boucart Island, Louth Bay, 268
 Boudeuse Island, 290, 291, 295
 Bounty Islands, 260, 262, 370
 Bourg Saint Andiol, 447
 Bowditch Island, 189
 Boyds Island, 147
Brachyphylla nana, 389
 Bramble Cay, 255, 274, 368
 Brampton Shoals, 257
 Brandenburg, 424
 Brava, 44, 395
 Brazil, 345, 346, 382
 Brazil Current, 352
 bread-nut tree, 391
 Breaksea Islands, 265
 breccia, 274, 322, 341, 347, 457, 478
 bone, 269, 330, 331, 347, 406, 408, 409, 431
 coral, 281
 shell, 153, 156, 280
 Bredasdorp coast, 134, 151
 Breezy Point, 392
 Brescia, 456
 Brewster County, Texas, 397
 Brewster's boobies, 132, 367
 bridled tern, 326
 Briggs, Arizona, 401
 British Columbia, 402
 British Guiana, 345
 British North Borneo, 411
 British West Indies, 331, 363
 Brno, 441
 bromine, 468
Brosimum, 391
 Brothers Islands, 267-269
 brown boobies, 133, 186, 196, 236, 291, 318, 326
 noddy, 326
 pelican, 20
 rats, 169
 Browse Island, 271, 470
 Bruck, 438
 brushite, 117, 119, 130, 132, 325, 334, 336, 343, 344, 391, 413, 422, 429, 434, 435, 449, 464-466
 Bryozoa, 266
 Buchan, Australia, 406
 Buco del Frate, 456
 Buco del Soglio, 456
 Budapest, 424, 429
 Bugarach, 445
 Buis-les-Baronnies, 445
 Bulacan, 413
Bulweria bulweri, 201, 202, 206
 Bunker group, 255, 257
 Bur-da-Rebschi, 303, 305
 Burgos, 451
 Burgurett, 420
 Burial Cave, Tennessee, 404
 burials, associated with guano, 46, 148
 Burma, 418
 Burnet County, Texas, 395
 Burr Creek, 409
 Bushy Island, 267
 buzzards, turkey, 33, 51
 Cabinzas Island, 52
 Cabo Falso, 325
 Cabo Rojo, 385, 387
 Čačak, 427
 cactus, 323
Cactus caesioides, 336
 Cadiz, 451, 452
 cadmium, 468
 Cagliari, 455
 Caja de Muertos, Puerto Rico, 327
 Calabria, 456, 461
 Calapan, 413
 calc, 73
 calcite, 339, 413
 calcium, 85, *passim*
 calcium carbonate, 107, *passim*
 calcium glycolate, 77
 calcium oxalate, 75, *passim*
 calcium oxide, 73, *passim*
 calcium phosphate, 3, *passim*
 calcium sulphate, 113, *passim*
 Caldera, 48
 caliche, 36, 85, 96, 98, 104, 112, 337, 464
 Calico, California, 401
 California, 401
 California Current, 122, 137
 Callao, 9, 21, 32, 52, 53
 Callao Painter, 11, 139
 Callaway County, Missouri, 403
Calophyllum, 191
Calothrix stellaria, 197
 Camarasa, 452
 Camargo, 395
 Camden County, Missouri, 402, 403
Camelops, 402
 camels, fossil, 402
Camerina, 227
 Campana, 390
 Campbell, Malay States, 417
 Campbell Cave, Africa, 420
 Campbell Island, 260
 Cambridge Gulf, 271
 Camuy, 385
 Canary Current, 157
 Canary Islands, 158
 Canellas, 452
 Canevaro, 28
 canoe, Washington Island, 184, 375
 Canton Island, 166, 177, 178, 180, 189, 190
 Cantores Islets, 29

- Cap Bernard, 422
 Cape Bougainville, 271
 Cape Catastrophe, 268
 Cape Colnett, 127
 Cape Comet, 392
 Cape cormorant, 129
 Cape Corso, 129
 Cape Couedie, 267
 Cape Cross, 157
 Cape Cross Bay, 134, 150
 Cape Frio, 352
 Cape gannet, 140-142
 Cape Guardafui, 303, 304
 Cape Kidnappers, 261
 Cape of Good Hope, 136
 Cape Pembroke, 358
 Cape penguin, 140
 Cape Peninsula, 137, 139
 Cape pigeons, 62
 Cape Point, 139
 Cape Province, 157
 Cape Rouge, 267
 Cape San Lucas, 132
 Cape Saunders, 262
 Cape Sir Grant, 265
 Cape Verde Islands, 158, 313
 Capiz, 413
 Capo San Elia, 456
Capreolina mayai, 249
 Capricorn group, 255, 257
Capromys nana, 389
 Caracas, 384
 Caracoles, 112
 carbon, 295, *passim*
 carbon dioxide, 77, *passim*
 carbonate-apatite, 337
 carbonate-hydroxyl-apatite, 327, 336
 carbonate-whitlockite, 343, 344
Carcharias, 298
Carcharodon, 210, 378
 megalodon, 214, 238, 338
 megalodon yamanarii, 238
Cardium fragum, 238
 Cargados Carajos Atoll, 288, 290, 293, 294, 299,
 302, 303, 373
 Caribbean Sea, 315-318, 322, 323, 332, 333, 362,
 363, 365, 371, 373, 376, 393, 482
 Caribees, 327, 328
 Carinthia, 438
 Caripe Cumaná, 384
 Carloforte, 455
 Carlsbad Caverns, 397, 398
 Caroline Island, Line Islands, 160, 167, 187, 373,
 374
 Caroline Islands, western Pacific, 208, 223, 227, 229
 Carpathians, 443
 Carretas Point, 44
 Casas Viejas, 452
Cassutha, 290, 371
 filiformis, 293, 294
 Castellón de la Plana, 451
 Castelvieu, 447
 Castilho Island, 353
 Castrovillari, 456, 461
Casuarina, 228, 293, 294, 299, 301
 Casuarina Islets, 267
 Cat Island, 266
 Catalina de Güines, 390
Catharacta skua chilensis, 20
Cathartes aura falklandica, 18
 Catos Island, 213
 cats, feral, 165, 175, 193, 273
 Cave Creek, Illinois, 405
 cave guanos, 381 *et seq.*
 Cave Ha, 457
 Cavinzas, 22
 Caxones, 319, 344, 376
 Cayenne, 346, 348
 Cayey, 387
 Cayman Brac, 320
 Cayman Islands, 318, 320, 344, 345, 362, 370
 Cayman Sea, 315-318, 321, 362, 363, 376
 Cayo de Agua, 336
 Cayo El Dorado, Orchilla, 334, 335
 Cayo Grande, 336
 Cayos de los Jardinillos, 323
 Ceara, 382
 Cedros Island, 122, 128
 Celebes, 276, 278, 284
 Celina, Tennessee, 404
 Centinella, 334, 345, table 54
 Central Chincha Island, 15-17, 19, 33-36, 38-41,
 43, 51, 68, 69, 71, 481
 See also Chincha Islands
 Central Massif, France, 444
 century plants, 323
 cephalopods, 263
Cereopsis, 268
 Cerro Azul, 22, 72
 Cerro de Arequita, Uruguay, 382
Cervus elaphus, 457
 Cesse River, 447
 Cesserias, 447
 Cevennes, 444
 Chabeuil, 445
 Chagos Archipelago, 293
 Chala Atico, 22
 chalcedony, 155, 275, 476, 478
 chamois, 439
 champignon, 215, 217, 296, 298, 303, 482
 Chanavaya, table 5, 82, 100, 106, 107
 Chancay, 44, 59
 Chañaral, 53, 54
 Chao Islands, 30, 31, 361
 Chara, 197
 Charadriiformes, 5, 366, 367

- Charadrius sanctae-helenae*, 313
 Charlotte Island, 213
 Chatham Island, 260
 Cheddar Caves, 457
Chelonia, 330, 411
Chenopodium sandwicheum, 202, 203, 205
 Chenoua-plage, 422
 Chester Islets, 126, 128, 129
 Chesterfield Islands, 253, 257, 258, 362
 Chia-u-su, 248
 Chiclana de la Frontera, 452
 Chihuahua, 395
 Chile, 9, *passim*
 Chiloe Island, 48
Chilonycteris rubiginosa mexicana, 395
 Chimote, 23
 China, 276-279, 282, 362-365, 371, 373, 376, 482
 Chíncha Islands, 9, 10, 21-23, 27, 33-44, 48-52, 54-57, 59-63, 65-72, table 5, 80-83, 85, 91-95, 106, 107, 150, 153, 355, 361-365, 379, 462, 464, 481
 See also Central Chíncha, North Chíncha, and South Chíncha Islands
 Chipana, 110
 See also Punta Falsa de Chipana
 chironomids, 327
 chiropterite, 381, 423-425, 428, 429, 431, 433, 434, 436, 437, 444, 447, 459, 472, 473, 480
 chitin, 5, 113, 381, 388, 406, 460, 462
 chlorapatite, 467, 468
 chloride, 85
 chlorine, 73, *passim*
 chlorite, 122
 Chlorophyceae, 197
 cholera, avian, 19
 cholesterol, 75
 Choros Islands, 53
 Christmas Island, Indian Ocean, 210, 276, 285, 291, 363, 376-378, 469-471, 473
 Christmas Island, Pacific Ocean, 163-165, 167, 182, 184, 191, 192, 194, 195, 269, 374
 chromium, 275, 478
 Chucumata, 99, 110
 Ciales, 385
 Cibolo Creek Cave, Texas, 396
 cicindelid beetles, 197
 Cima Island, 158
 cirolanid, 420
 Clauzel, 423
 clay, 115
 Clay County, Tennessee, 404
 clinobarrandite, 475
 Clipperton Island, 125, 158, 160, 194-197, 362, 476, table 54
Closterium parvulum, 197
 parvulum var. *majus*, 197
Clostridium acidi-urici, 77
 Clupeidae, 86
 Coahuila, 395
 Coast Range, Venezuela, 333
 cobalt, 423
Cochlearia, 370
 Cochon Island, 358
 cockroaches, 420
 coconuts, 166, 177, 178, 182-185, 187, 191, 208, 212, 219, 223, 229, 236, 257, 258, 293-296, 320
Cocos, 163, 370
 nucifera, 186
 nucifera f. *palmyrensis*, 185
 Cocos Island, 196
 Cocotea, 22, 44, 45
 Coffin Bay, 268, 269
 Coffin Rock, 128, 129
Colaptes auratus, 77
 Coleoptera, 420, 456
Coleura afra, 420
 Colleda Cave, Missouri, 403
 Collier Bay, 274
 Collingwood District, 410
Collocalia, 381, 411
 fuciphaga, 411
 collophane, 221, 313, 413, 434, 435, 438, 469, 470
 collophanite, 299
Colobanthus muscoides, 262, 370
 Colombia, 381
 Colonial Islands, 126, 135-137, 142, 143, 145, 149, 151, 152, 362
 Colorada Island, 26-28
 Colorado, Gulf of California, 128, 129
 Colorado, Punta Gruesa, 98
Columba livia, 411, 422
 Comal County, Texas, 395
 Comarca, 382
 Comayagua, 384, 463
 Comerío, Puerto Rico, 385
 Comoro Islands, 288
 Concordia, 67
 condor, 18, 33
 conglomerate, 30, 34, 184, 185, 203, 212, 221, 246, 298
 Connétable, 473, 476
Conopoderas, 167, 212
 aequinoctialis, 167
 aequinoctialis aequinoctialis, 167
 aequinoctialis pistior, 167, 375
 atypha, 210
 atypha atypha, 212
 atypha erema, 210
 atypha niauensis, 212
 familiaris, 201, 206
 kingi, 201
 vaughani taiti, 212
 Conques, 447
 Consag Rock, 129
 Consagra Rock, 129, 130
 Consolation, 446

- Constable Hill, 155, 156, 475, table 54, 477
 Constantine, 423
 Constitución Island, 47
 Controne, 456
 Cook Islands, 163, 208
 coot, 187
 copper, 340, 415, 461, 474, 476
 copra, 183, 188, 229
 coprolites, 4, 381, 458
Coprosoma, 263
 Coquimbo, 21, 54
 coral (and coral rock), 167, 170, 172-176, 181, 183-186, 191-195, 197, 205-212, 214-217, 219-223, 226, 228-232, 235, 236, 240, 247-250, 253, 255-259, 271-273, 278, 280-282, 284, 285, 291, 292, 295-302, 307, 315, 319-323, 325, 328, 331, 333-342, 347, 376, 377, 392, 421, 465, 470, 471, 475, 482
 Coral Island, 181, 321
 Coral Sea, 253, 255, 257
 Corcovado, 31, 83, 361
Cordia, 166, 168, 177, 178, 191, 371
 subcordata, 168
 Cordillera de Merida, 382, 383
 cormorant, Cape, 129
 cormorants, 5, 47, 53, 54, 59, 60, 62, 64, 104, 124-127, 140, 141, 265, 266, 275, 356, 366, 370, 478
 Cornejos, 31
 Cornwallis Island, 186
 Coro, 333
 Coroca, 134
 Corral Velho, 158
 Corsica, 452
Corvus corax sinuatus, 131
Corynebacterium ureafaciens, 77
Corynorhinus, 394
 rafinesquii townsendii, 402
Cosmarium clippertonensis, 197
 subprotumidum, 197
 Cosmoledo, 288, 290-292, 297, 302, 368
 costra, 96
 Cotar Island, 181
 Cote d'Or, 444
 Coues gadwall, 167
 Councillor Island, 265, 266
 Cova del Tabaco, 452
 Cova dels Muricets, 451, 452
 Cova den Rubí, 452
 Cova negra de Tragó, 452
 crabs, 196, 290
 Cracow, 443
 cranes, 255
 Crawford County, Indiana, 403
 Crawford County, Missouri, 403
 crayfish, 144
 creatin, 422
 creepers, 226
 Crescent group, Paracel Reefs, 279
 Crest Sud, 447
 crickets, 420
 Crustacea, 19, 411, 420
 Csoklovina Cave, 428, 464, 465
Ctenomys, 112
 Cuba, 317, 322, 344, 389
 Cuchillo, New Mexico, 398
 Cueva, Pabellón de Pica, 102, 108
 Cueva Catedral, Morovis, 385, 389
 Ceuva de abaho del Collorada, 451
 Cueva de abaho de las Guixas, 451
 Cueva de la Punta de Beninaquia, 452
 Cueva de los Indios, Cuba, 389
 Cueva de Oriamendi, 452
 Cueva del Argar, 452
 Cueva del Churreron, 452
 Cueva las Piedras, 384
 Cuevas del Drach, 452
 Cuevitas, 112, 113
 Ciudad Real, 451
 Culaca, 98
 Cumberland Mountains, 404
 Curaçao, 287, 318, 333, 337, 338, 345, 362, 363, 376-378, 466, 469-474, 476
 curlew snipe, 187
 curlews, 187
 Curta Rocks, 268
Cynonycteris collaris, 420
 sjöstedti, 420
Cyperus, 205
Cytosperma chamissonis, 184
 Czechoslovakia, 441, 443, 461
 Dachlluken, 439
 Dachsteinrieseneishöhlen, 441
 dacite, 329
Dafila modesta, 167
 Dahlak Archipelago, 307
 dahllite, 327, 336, 337, 347, 413, 469, 470, 477
 Daiquiri, 389
 Daito Islands, 246, 252, 366, 377
 Daizingu-yama, Kita Daito Jima, 240
 Dalby Island, 267
 Damaraland, 134, 150
 damsel flies, 197
 Danger Island, 189, 190
 Dangerous Ground, 276, 282, 365, 376
 Dangerous Reef, 268
 Dangers Rock, 189
Daption capensis, 262
 Dard Valley, 447
 Dar-es-Salaam, 303, 305
 Dark Canyon, Nex Mexico, 399
 Darling Division, 157
 Dassen Island, 136, 140, 143, 145, 151, 152
 Dato Island, 285
 David Island, 189

- deer, 249, 457
 red, 457
 Deming, New Mexico, 398
 Denia, 452
 Denial Bay, 267, 269
 Dennis Island, Seychelles group, 288, 293–296,
 302, 371
Densinyama, 227
 Dent County, Missouri, 403
 D'Entrecasteaux Reefs, 258
Dermanyssus, 112
Dermonotus davyi, 395
 Des Petits Andelys, 444, 446
 Desecheo Island, 318, 325, 344, 345, 376
 desmids, 197
Desmodus rotundus murinus, 395
 Desnoeufs Island, 290, 291, 295
 Desroches Atoll, 295
 Devil's Coachhouse, New South Wales, 408, 409
 Devils Riding School, Ascension, 311
 Devonshire, 458
 diabase, 336, 348, 349, table 54
 Diamant, 344
 diatoms, 112, 122, 123, 137, 139, 197, 307
 Diego Ramirez Island, 353, 355
 Dingle, 413
Diodon, 298
Diomedea albatrus, 237, 366
 bulleri, 262
 cauta, 366
 cauta cauta, 264, 265
 cauta salvinii, 263
 exulans, 263
 immutabilis, 186, 200–203, 205–207, 236, 366,
 368
 nigripes, 166, 186, 200–203, 205–207, 236, 366
 diorite, quartz, 341
 Diptera, 420
 Dique, 100
 dittmarite, 407, 408, 474
 divers, 62
 diving petrel, 5, 23
 dog, 457
 Doldrums, 7, 8, 364
 dolerite, 477
 dolomite, 211, 214, 216, 217, 219–222, 286, 343,
 377, 378, 380, 413, 473
 Dombicza Cave, 431
 Domico, 461
 Domusnovas, 455
 Don Martin Island, 21–23, 31, 48, 56, 75, 76
 Donkin's Bay, 151
 Donnington Island, 268
Dorcasia limestone, 153, 156
 Dordogne, 444
 Dorgoli, 454, 455
 Doubs, 444, 446
 Doughboy Islands, 266
 Douglas Bay, 146
 doves, 381, 422, 439
 wild rock, 411
 Drachenhöhle, 381, 424, 430–438, 442, 458, 459,
 462, 464, 472, 473, 480
Dracoena, 297
 reflexa, 297
 Dra-el Mizan, 422
 Drátenikova Cave, 441, 443
 drepanid, 201
 dripstone, 431, 439
 Drôme, 444, 445, 447
 Drummond Island, 282
 Ducie Island, 213
 ducks, 167, 336, 457
Ducula aurorae, 210
 Duffield Island, Louth Bay, 268
 dufrenite, 349–351, 478
 duiker, trek, 140, 141, 144
 Duiker Klip, 151, 152
 Duke of Clarence Island, 189
 Duncan Island, 282
 Dunedin, 262
 dunite, 346, 347
 Durango, 395
 durian, 418
 Durour Island, 226
 Dutch Borneo, 412
 Dutch Leeward Islands, 318, 332, 337, 338
 Dutch West Indies, 315
 Dyer's Island, 134, 151, 152
 Eagle Island, Amirante Islands, 295
 eagles, 274, 478
 East Africa, 419
 East Cay, Serranilla Cays, 321
 East Guano Cay, 322
 East Island, The Snares, 262
 East North Island, Cosmoledo, 291, 292
 Easter group, 273, 274
 Eastern Cove, Australia, 267
 Eastern Islet, Midway, 207
 Eastern Islet, Palmyra, 186
 Eberhardt Cave, Last Hope Inlet, Patagonia, 382
 Eboli, 456, 461
 Ebon, 228, 229, 250, 251, 373, 374
 echinoderms, 273, 278, 298
 Eddy County, New Mexico, 399
 edible-birds'-nest bird, 411
 Edwards County, Texas, 395
 eels, 139
 egesta, 3, *passim*
 Egg Island, St. Helena, 315
 Egg Islands, Clipperton, 197
 egg-bird, 314
 Eggenburg, 439
 Eggerloch, 438
 Egypt, 381, 422, 462

- Eil Malk, 232, 252, 377, 378
 El Colorada, 31
 El Dorado Island, 31
 El Dorado Islet, Orchilla, 376
 El Encantado, near Caracas, 384
 El Fondo, 388
 El Ghar, 422
 El Gran Roque, 333
 El Indio, 389, 390
 El Infernillo, Vera Cruz, 395
 El Infierno, 390
 El Morro, Isle of Toas, 384
 El Niño, 13, 53, 139
 El Olivo, Isle of Toas, 384
 El Paso, Texas, 396
 El Pelado, Huaura group, 32, 59, 60, 63
 El Pintor, 11
 El Toro, Mona Island, 327
 El Toyo, 98, 99
 Ela de Cerros, 128
Elainea ridleyana, 347
 Elandsfontein, 419
 Elder Rock, 274, 477, 478
 elephant molar, 247, 249, 378
 Elephant Rock, 136, 151, 152
 Elephant Rocks, 265
 elephant seals, 128
Elephas trogontherii, 249
 Elide Island, 122, 126, 128–130, 475
 Elizabeth Bay, 146
 Elizabeth Island, 208, 212, 213
 Elizabeth Island [Alim Island], 226
 Elopura, 410, 411
Emoia arundeli, 197
 cyanura, 197
 Enderbury Island, 177–180, 193, 364
 England, 424
 See also Great Britain
 English Bay, 313
 English Island, 268
Engraulis, 56, 58
 encrasicholus, 86, 87
 mordax, 124
 ringens, 14, 19, 86, 88
 Eno River, 396
 epiglaubite, 343
Eptesicus fuscus, 404, 405
 hispaniolae, 389
 nilssonii, 424, 433, 434
 serotinus, 443
 Equatorial Counter Current, 5–7, 13, 120, 121,
 160, 288, 345
 Erabu Shima, 249
Eragrostis variabilis, 205, 207
 Erfsendorf, 441
 Eritrea, 306
 Erizos, 31
 Ermelo, 419, 480
Erythroxylon, 293
 Espirito Santo, 382
 Espluga de Las Tosas, 451
 Esprit, Aldabra, 297–299, 303
 Establishment Island, Cargados Carajos, 293
 Étoile Island, 290, 291, 295
Eudiptes crestatus, 358
 crestatus filholi, 262, 263
 pachyrhynchys, 262
 sclateri, 263
Eudiptula minor novae-hollandiae, 265
Eulepidina, 227
Eupritchardia vuylstekeanum, 210
 Eure, 444
 Europa Island, 301, 302
 Europe, cave guano, 423 *et seq.*
 Eva, Tonga group, 222
 Evans Island, 269
 evansite, 275, 478
 excavations, Howland Island, 184
 excreta, 3, *passim*
Exocoetus, 291
 Eyres Island, 269

 Fabre Island, 258
 Facing Island, 274
 Fagan Pissila, 227
 Fairfax Island, 255–257
 fairy penguins, 265
 prion, 265
 Fais Island, 299, 230, 234, 251, 252, 376–378
 Fakaofu, 189–191
 Falkland Current, 353
 Falkland Islands, 353, 357–359, 366
 False Bay, 134, 139, 141, 151, 152
 Fanaadir Island, 307
 Fanning Island, 163–167, 183–185, 188, 190, 192,
 194, 195, 213, 364, 370, 373–375, 470
 Farallon de San Ignacio, 124–126, 131, 132, 344,
 362, 465
 Farmer Island, 189
 Farquhar Atoll, 288, 290–292, 296, 302, 368, 475
 Favorite Island, 189
 Faywood, New Mexico, 398
 feldspar, 122, 155, 198, 202, 477
Felis, 450
 Felix Gonzales Island, 26, 27
 Fernando de Noronha group, 345–347, 352
 ferns, 223, 226
 ferric aluminum phosphates, 90, *passim*
 ferric hydrates, 244
 ferric oxide, 82
 ferric phosphate, 115, *passim*
 Ferrol Islands, 31
 Feys, 229
 field mouse, long-tailed, 433
 Figeau, 449
 Fiji, 187, 188, 210

- Fillmore, Utah, 402
 Filomena Cave, 412, 414
 fish-eating bats, 381, 385, 393
 flamingos, 36, 43, 59, 336
 Flat Island, China Sea, 283, 284
 Flat Island, Red Sea, 307
 Flaxbourne, 410
 Fledermaus Grotto, 443
 flies, 19, 197, 264, 369, 405
 damsel, 197
 Flinders Island, 265, 269
 flint, 306
 Flint Island, 160, 164, 167, 187, 189, 190, 208,
 362, 373
 Flores, 276, 278
 Flores Sea, 276, 285
 Florida, 394
 fluorapatite, 157, 346, 347, 467–469, 471
 fluorine, 85, *passim*
 flycatcher, 214
 flying fish, 291
 flying foxes, 420
 Flynn's Lick, Tennessee, 404
 Fontein, 338
 Foraminifera, 238, 273, 286, 298
 Formiga, 382
 Forming Island, 183
 Formosa, 249
 fox, 457
 France, 424, 425, 444
 Frances Island, 189
 Francis Island, 189
 Francisco Quiñones, San Germán, 386, 387
 francolite, 221, 274, 469–471, 473, 482
 Frankenfels, 439
 Franklin County, Tennessee, 404
 Franklin Island, 269
 Franklin Sound, 266
 Frassassi, 456
 free-tailed bats, 393, 424
Fregata, 89, 171, 175, 212–214, 256, 313, 314, 320,
 333, 348, 352, 367
 andrewsi, 286
 aquila, 202, 236, 311, 313, 314
 ariel, 313, 314
 ariel trinitatis, 313, 314
 magnificens, 53, 313, 314, 347
 magnificens lowei, 313, 314
 magnificens rothschildi, 26, 318, 320, 326, 333,
 334
 minor, 236, 272, 285, 313, 314
 minor minor, 279, 286
 minor nicolli, 313, 314
 minor palmerstoni, 166, 201–203, 205–207
 Fregatidae, 366
Fregetta g. grallaria, 120
 French Alps, 446
 French Frigate Shoals, 198, 200, 204, 205
 French Guiana, 345, 346, 348
 French Guinea, 158
 French Pyrenees, 445
 Frienhaven, 189, 190
 frigate bird, Ascension Island, 311
 frigate birds, 165, 175, 181, 187, 197, 203, 206,
 248, 256, 284, 291, 313, 352, 367
 Frigate Island, Cargados Carajos, 293
 Fronton Island, 21–23
 fruit-eating bats, 381, 385, 387
 Fuchs, 439
 Fuchsloch, 441
 Fuller's earth, 319
 Furneaux group, 266
 gabbro, 337
 gadwall, 167
 Coues, 167
 Gaferut, 229, 250, 251, 374
 Gailenreuth, 444
 Gairo, 455, 456
 Galápagos Islands, 29, 121, 330
 gallinazo, 18
 Gambian coast, 314
 Gambier Islets, 268
 Gamboola Caves, 409
 Gaming, 439
 Gamslöcher, 441
 Ganges Island, 189
 Gannet Hill, Christmas Island, 287
 gannet, Australian, 266
 black, 259
 Cape, 140–142
 gannets, 5, 51, 62, 144, 187, 261, 305, 308
 Gap, Malay States, 415
 Gard, 444, 446, 447
 Gardner Island, 164, 177, 178, 189, 198, 205
 garruma, 112
 Gaspar Rico Atoll, 227, 228, 250
 gastropod, 238
 Gaviota, 128, 129
Gecarcinus planatus, 196
 Geldloch, 439
 Gente Hermosa, 190
 gentoo, 358
Geocapromys columbianus, 389
 Georges Island, 124–126, 129
 Georgetown, 313, 320
 Georgia, 394
 Gerlock, Nevada, 401
 Germany, 423, 424, 443
 Gerona, 451
 Geronimo Island, 127
 Gherirat ul Humr Island, 310
 Ghetarul dela Barsa, 427
 giant petrels, 263, 370
 sloth, 404, 405
 Gibraltar, 451

- Giggleswick, 457
 Gila River, Arizona, 401
 Gilbert Islands, 208
 Gillespie County, Texas, 395
 Glaserluke, 437
 glauapatite, 343
 glaukerite, 204
Gleocapsa, 411
Globigerina, 226
 globosite, 275
 Glorioso Island, 291, 299
Glossotherium, 382
 glycolic acid, 77
 glyoxalic acid, 77
 gneiss, 269, 348, table 54
 granite, 305
 hornblende, 306
 Gng Hapoe, 412
 Gng Lampinet, 412
 Gng Pawon, 412
 Goa Mempi, 416, 417
 Goa Sammy, 416-418
 Goat Island, 269
 goats, 313, 457
 Godfreys Island, 267
 Goelette Island, 290, 291, 296, 302
 Gösing, 439
 Goinanton, 411
 goney, 166, 186
 Gonzales Islet, 120
 goose, 457
 Gorenice, 443
 Gough Island, 353
 Government Guano Islands, 140-142, 145, 149
 Gramandal, 31
 Gran, 429
 Gran Roque, 336, 337, 345, 376, 475, 476, table 54, 477, 478
 Granada, 451
 Grand Canyon, 401
 Grand Cayman Island, 318, 320
 Grand Connétable, 346, 348, 475, table 54
 Grand Turk, 392
 granite, 26, 33, 40, 103, 113, 115, 116, 153, 155, 262, 263, 266, 268, 305, 306, 322, 333, 353, 415, 466, 476, table 54, 477
 Granite Range, Nevada, 401
 granodiorite, 333
 Grass Valley Creek, Nevada, 401
 Grau, 429
 Gravata Islet, 352
 Graz, 431, 437
 Grazalema, 452
 Great Barrier Reef, 253, 255, 256, 362, 365, 368
 Great Bight, 269
 Great Britain, 457
 See also England
 Great Camanoe, 327
 Great Cayman, 319
 Great Detached Reef, 255
 Great Ganges Island, 189
 Great Northeast Channel, 255
 Great Paternoster Point, 151
 Great Sandy Island, 272
 Great Swan Island, 319
 Great Wyandotte Cave, 403
 Greater Antilles, 315, 318, 322
 Green Island, 266
 Green Islet, 262
 Green Islet, Midway, 207
 Green Islet, New Zealand, 478
 Green Mountain, Ascension, 311, 312
 Greenbrier County, West Virginia, 405
 Greenby Island, 268
 Greenland, 369
 Greenwich Atoll, 229, 250, 251, 373, 374
 Greenwich Canyon, Utah, 402
 Grenada, 332
 Grimes Island, 229, 250
 Grindal Island, 268
 Gronique Island, 189
 Grosse Peggauer Felsenhöhle, 437
 Grosswardein, 428
 Grotta Biddiriscottai, 454, 455
 Grotta Boe Marinu, 454
 Grotta Coazza, 454
 Grotta Conca Ruia, 454
 Grotta de San Giovanni di Domusnovas, 455
 Grotta de Sadini, 453
 Grotta dei Colombi, 455, 456
 Grotta dell' Inferno, 452, 453
 Grotta di Borutta, 453
 Grotta Gologone, 454
 Grotte aux Pintades, 421
 Grotte d'Arbon, 446
 Grotte de Baume-des-Messieurs, 447
 Grotte de Beni-Add, 422
 Grotte de Beure, 446
 Grotte de Cabéou, 446
 Grotte de Ganties, 446
 Grotte de Gazel, 447
 Grotte de la Calmetter, 446
 Grotte de la Coquille ou de Minerve, 445, 447-449, 464, 472, 474, 479, 480
 Grotte de Mollans, 445
 Grotte de Peyroche, 445
 Grotte de PIALoux, 445
 Grotte de Pietralbello, 452
 Grotte de Ponte Leccia, 452
 Grotte de Remène, 445
 Grotte de Senchet, 445
 Grotte de Tharaux, 446
 Grotte de Tourtouse, 447
 Grotte des Cavottes, 446
 Grotte des Chauves Souris de Janoy, 446
 Grotte des Tignahustes, 424

- Grotte D'Isturits, 447
 Grotte du Lac Souterrain, 423
 Grotte du Mas d'Azil, 445
 Grotte du Prince, 458
 Grotte du Rendez-vous de Chasse, 446
 Grotte du Soldat, 445
 Grotte du Sureau, 447
 Grotte du Veau Marin, 422
 Grotte inférieure du Queire, 445
 Grotte Sainte-Catherine, 446
 Grottes de Grimaldi, 458
 Grotto Cave, 408
 ground sloth, 398, 401
 Gruetas, 113, 462
 Grute de la Algareta, 451
 Guacharo Caves, 384
 Guadalupe, 332
 Guadalupe, 128
 Guadalupe Mountains, 397
 Guajes, 98
Guanaes, 62
 Guanahani Island, 392, 393
 guanapite, 91, 92, 463
 guanay, 3, 14-21, 28-33, 44, 48-51, 53-55, 59, 60, 63-67, 73, 74, 87, 88, 125, 129, 141, 367, 369
 guanera, defined, 3
 guanidine, 77
 Guanillo, 48
 guanine, 72, 77, 81
 guanite, 153
 guano, 3, *passim*
 ancient, 3, *passim*
 cave, 381 *et seq.*
 concrete, 80, 153
 decomposed, 3, *passim*
 leached, 3, *passim*
 modern, 3, *passim*
 nitrogenous, 3, *passim*
 old, 3, *passim*
 phosphatic, 3, *passim*
 saline, 80, 85, 106, 153
 guano blanco, 48
 colorado, 114, 462
 deposition, biological conditions for, 4
 geophysical conditions for, 5
 glass, 28, 29, 121
 pobre, 71
 Guano Cay, 331
 Guano Island, 327
 Guano Islet, Shark Bay, 273
 guanosterol, 75
 guanovulite, 92, 94, 463
 guanoxalite, 94, 463
 Guafape Islands, 19-23, 29, 30, 34, 42, 48, 51-53, 56, 63-67, table 5, 81-83, 86, 89, 91-93, 95, 106, 118, 150, 151, 355, 463, 464, 481
 Guardian, Pabellón de Pica, 102
 Guayaquil, 13, 53, 54
 Guernica Central, 385
 Gugong Tunggal, 415
 Guianas, 315
 guillemots, 361
 Guimaras, 413
 Guipúzcoa, 451, 452
 Gulf of Aden, 303, 304
 Gulf of California, 123-125, 130, 131, 344, 362, 367, 368, 465
 Gulf of Carpentaria, 255
 Gulf of Maracaibo, 342
 Gulf of Masirah, 310
 Gulf of Mexico, 317, 318
 Gulf of Panama, 120
 Gulf of Tonkin, 278
 gulls, 5, 18, 33, 52, 60, 61, 88, 112, 125, 142, 144, 187, 256, 265, 266, 307, 327, 352
 Gun Island, Pelsart group, 274
 Gundersheim, 425, 444
 Gunong Pondok, 415
Gygis, 165
 alba, 187, 210, 213, 214, 236, 313, 314, 347, 370
 alba alba, 311
 alba candida, 165, 185, 197, 201-203, 205-207, 212, 213, 293
 alba kittlitzii, 210
 alba monte, 291, 293
Gyna, 420
 kazungulata, 420
 vetula, 420
 Gyor, 429
 gypsum, 33, 117, 119, 131, 132, 150, 153, 172-174, 180, 204, 319, 322, 327, 332, 340, 355, 356, 393, 401, 408, 429, 436, 447, 449, 461, 463, 465, 467
 Gypsum Cave, Nevada, 400, 401
 Habana, 390, 391
 Hacienda Juanita, 385
 Margareta, 387
 Haderuma Jima, 249, 251, 252
 Hadji Prodanova pećina, 427
 Hadramaut, 305
Haematopus ater, 62
 ostralegus pitanay, 62
 Hagu-ue plateau, Kita Daito Jima, 238, 240
 Haile Cave, Tennessee, 404
 HaItajwa Cave, 420
 Haiti, 325, 363, 388
Halcyon gambieri gertrudae, 212
Haliaster indicus, 411
 Halifax Island, 140, 146, 147
Halimeda, 227, 286
 halite, 119
Halocyptena microsoma, 128
 halogens, 468, 473, 476
 Hamilton, Australia, 406

- Hamman Meskoutine, 423
 Ham-Ron, 413
 Hanish Islands, 307, 308
 hannayite, 406–408, 474
 Harbi, Mahabbakah Islands, 307, 308
 harbortite, 349–351, 478
 hare, 457
 Hareby Island, 267
Harengula thrissina, 124
 Harimizu Harbor, Miyako Jima, 249
 Harrison County, Indiana, 403
 Hartlesgraben, 438
 Haski Island, 308, 309
 Hasyokan Island, 249
 Hateruma Jima, 249, 377, 378
 Hatillo, 385
 Haugsbrung Valley, 420
 Haut Sebaou, 422
 Haute Garonne, 446
 Haute Saône, 444
 Hautes Pyrénées, 424, 445
 Hawke Bay, 261
 hawks, 411
 Hawaiian Islands, 198, 202, 207, 208, 313
 Hawaiian Leeward Islands, 160, 198–202, 207, 362, 365, 366, 370, 371
 Hays County, Texas, 395
 heguiro, 63
Heliotropium curassavicum, 196
 hematite, 274
 Henderson Island, 208, 376, 378
 heraldic slab, under guano, 69, 70
 Hérault, 444, 446, 447
 Herdenglhöhle, 439
 Hergest Rocks, 181
 Hernani, 452
 herons, 36, 43, 59, 187, 336
 blue, 290
 heterauxin, 75
Hibiscus, 296
 Hidalgo County, New Mexico, 399
 Hieffau, 438
 Highland Rim, Tennessee, 404
Himatione freethi, 201, 205, 206
 Hispaniola, 317, 322, 388
 Hobart Town, 265, 273
 Hobbies, 319
 Hobbie Canyon, Utah, 402
 Hoecker Cave, Missouri, 403
 Hoedjes Point, 153
 Höhlenfels, 444
 Höllturmhöhle, 439
 Hohen Wand, 439
 Holborne Island, 253, 256
 Holbourne Island, 256
 Holdfast Tom, St. Helena, 314
 Holei Islet, Palmyra, 186
 Hollam's Bird Island, 140, 143, 146–148
 Holland, 331, 370, 423
 Honduras, 319, 320, 384, 463
 honeyeater, Laysan, 205
 Hopkins Island, 268
 Hormigas de Afuera, 21, 22
 hornblende, 333, 353
 Hornby's petrel, 112
 Hornillos, 44
 horses, 402
 horseshoe bats, 423
 Hoskyn Islet, 257
 Hottentots Bay, 134
 Hout Bay, 151
 Houtman's Abrolhos, 270, 271, 273, 368, 371, 470
 Howland Island, 163–170, 172, 174, 179, 184, 186, 193, 194, 250, 251, 364, 368, 370, 374, 379
 Huache, 52
 huanaes, 60
 huanay, 3
 huanera, 3
 Huanillos, 22, 70, 96, 104–107, 109, 118, 470
 huano, 3
 huanu, 3
 Huarmey, 23, 31
 Huaura Islands, 22, 23, 32, 48, 52, 60, 81
 Huesca, 451
 Hull Island, 164, 165, 177, 178, 189
 ul Hummer, 310
 Hummer Island, 310
 Hummock, 268
 Humphrey Island, 189
 Hundsalz, 441
 Hungary, 424, 428, 429, 431, 443
 Hung-Hoa, 413
 Hunter Cave, 394
 Hunter Island, 265
 Huntsville, Alabama, 402
 Huon group, 258, 259, 362
Hyaena crocuta spelaea, 450, 458
 hydrochloric acid, 153
 hydrogen sulphide, 11
 hydroxylapatite, 72, 89, 117, 180, 327, 336, 343, 464, 465, 468–470
 hydroxyl-carbonate-apatite, 470
 hydroxyl-fluor-apatite, 157
 hydroxyl-fluor-carbonate, 221
 hydroxyl-fluor-carbonate apatite, 221
 hyena, cave, 458
 spotted, 458
 hyenas, 418, 450, 458
 hypersthene, 329
 hyrax, 420
 Iberian Peninsula, 424, 451
 Ichabo, 91–93, 140–143, 146–151, 332, 463, 464
 Idaho, 402
 Ierzu, 455, 456
 Ifri Ivenan, 422

- Ifri-bou-Tigherset, 422
 Ighiu, 428
 Iglesias, 455
 Ihleu das Cabras, 155, 311, 315, 475, 476
 Ikema Shima, 249
 Ile à Fleur d'Eau, 181
 Île de Corail, 158, 476, table 54
 Ile de Sable, 181
 Île du Lise, 299
 Île du Nord, 280
 Île Glorieuse, 299
 Ilha Ancora, 352
 Ilha Cagarra, 352
 Illinois, 394, 405
 Ilo, 43, 44
 Îlot de la Perle, 328, 329, 344, 476, table 54
 Îlot Diamant, 329
 Imperial Cave, New South Wales, 408
 Inañi, 22
 Inca tern, 21
 Independencia Bay, 21, 22, 44, 48, 70, 82, 83, 95, 107
 Indian Ocean, 215, 276, 288, 301, 302, 362, 363, 365, 367, 370–373, 376, 421
 Indiana, 394, 403
 Indo-China, 276, 413
 Infiernillo, Pabellón de Pica, 102, 108
 Infiernillos, 23
 Ingersoll, 247
 Ink Cave, Missouri, 403
 Inlalapid Cave, 413
 insectivorous bats, 381, 385, 389, 391, 394
 insects, 4, 185, 201, 293, 381, 383, 384, 388, 402, 410, 419, 452–454, 461
 invertebrates, 262
 Investigator group, 269
 iodine, 91, *passim*
Ipomaea, 207, 272
 indica, 205
 pes-caprae, 205
 Iquique (town), 46, 59
 Iquique Islands, 36, 43, 45–49, 67, 361
 Ireland, 359
 iron, 241, *passim*
 Iron County, Utah, 402
 iron oxide, 325
 iron pan, 245
 iron pyrites, 325
 ironstone, 349–351, 382
 Irrawaddy, 418
 Isabela, Puerto Rico, 385
 Isabela Island, Philippines, 413
 Isabella Island, 133, 196
 Isère, 444
 Isla Blanca del Norte, 21, 22, 31
 Isla Chata, 356
 Isla Colorada, off Lobos de Tierra, 62, 66
 Isla de Cerros, 128
 Isla de Guana, 46
 Isla Gaviotas, 132
 Isla Grande, 48
 Isla Leones, 354–356, 478, 479
 Isla Pajaros, 31, 125–127, 129
 Islas de Aves, 318, 333, 335
 Islay, 22, 44, 45, 51
 Isle des Phoques, 266
 Isle Julien, 151, 152
 Isle Marens, 151, 152
 Isle of Pines, 323, 390
 Isle of Toas, Venezuela, 383
 Islote Perico, 21, 22, 26
Isolobodon, 389
 Isolotti Mohabbakah, 307
 isopods, 420
 Isratu Island, 307, 308
 Italy, 424, 456
 Itu Aba Island, 283, 284
 Iza, 43
 Jaboerukku, 228
 Jaca, 451
 jackals, 418
 Jackson County, Illinois, 405
 Jackson County, Tennessee, 404
 Jáckýmka Cave, 441, 443
 Jacob Reef, 136, 151
 Jalapa, 395
 Jamaica, 317, 320, 322, 323, 391–393
 Jamestown, St. Helena, 311
 Japan, 223, 227
 Jarvis Island, 82, 163–167, 170, 172, 174, 180, 181, 186, 193, 364, 465
Jasus lalandii, 144
 Java, 285, 412
 Java Sea, 276
 Jenolan Caves, 408, 479, 480
 Jerzmanowice, 443
 Jesús, 22, 44, 45, 51
 Jezirat Hallanyia, 308, 309
 Jezirat Kabliya, 308, 309
 Jibleea, 309
 Jimenez, 395
 Jíngemí Cave, 410
 Joao de Nova, 296
 João de Nova, Mozambique Channel, 299
 Johnny penquin, 358
 Johnston Island, 160, 163, 166, 167, 186, 362, 366
 Jonacatapec, 395
 Jones Island, 271
 Jote, 105
 Joubusuan, 410
 Juan de Nova, 299, 300, 302, 364, 376, 470, 473
 Juana Diaz, 385
 Jura, 444, 447
 Jutten Island, 140, 141, 151, 152

- Kabia, 285
Kahoagan Island, 413
Kakabia, 285
Kal Farun, 303–305
Kamaran Island, 306
Kaminone Shima, 248, 250
Kanehi, 212
kangaroo, 269
Kangaroo Island, 267, 269
Kansas, 393
kaolin, 116, 341, 350, 477
Kapellenhöhle, 438
Kapenmailang, 229
Kapiaganarangi, 229
Kapong Reman, 416
Kapulauan Island, 413
Karrenfeld, 210, 213–217, 219–222, 230, 246, 252, 286, 298, 303, 339, 344, 376–378, 482
Kasirah Island, 310
Katerloch, 438
Katmai, 472
Kauai, 200
Kaula, 198, 202
Kaut, 410
Kawi Kawyang, 285
Kealia, 200
Kedil Island, 232
Kemins Island, 189
Kemns Island, 189
Kents Cavern, 458
Kentucky, 394, 405, 464
Kenya Colony, 420
keratin, 74
Kerr County, Texas, 395
kestrels, 457, 458
Khorya Morya Islands, 308
Kidney Island, 358
Kikai Shima, 248
Kikai-ga Shima, 248
Kilwa, 420
King Island, 265, 266
King Sound, 272
kingfisher, 212
Kingman Reef, 189
Kiriteinerthal, 441
Kirkby Island, 267
Kirkdale, 458
Kirkly Island, 267
Kita Daito Jima, 236, 237, 241–246, 251, 252, 363, 376–378, 474, 476, table 54
Kita Oagari Jima, 237
kites, 411
Kiwa, 412
Kizimkari Reef, 304
Kloewang, 413
Kluitjiesfontein 369, 477
Knysna, 139
Kobi-Shima, 248
Kobito, 248
Kodogubi Island, 232
Köflach, 438
Koganeyama, Kita Daito Jima, 238, 240, 241
Kollerhöhle, 439
Konebusaki, Kita Daito Jima, 240
Kou trees, 168, 169
Kozarnia, 443
Krakatoa, 259
kraurite, 349
Kreefte Baai, 155, 156
Kremsmünster, 439
Krugersdorp, 418
Kuantan, 416
Kuba Shima, 248
Kufstein, 441
Kulumuzi, 420
Kunene River, 134, 141
kupatea trees, 175
Kure Island, 207
Kurema Shima, 249
Kuria Muria Islands, 308, 310, 362, 365, 475
Kurobuzaksi, Kita Daito Jima, 237
Kusakaki Shima, 247, 250
Kyaukse, 418

La Asunción, 126
La Bastide-Clairence, 447
La Busca Vida, 390
La Chira, 22
La Cocina, 22
La Cordillere, Venezuela, 383
La Cruz Island, 22
La Guaija, 99
La Guaira, 333
La Majina, Limon, 385
La Marguerite, Venezuela, 382
La Miel, Venezuela, 382
La Paz Bay, 132
La Perousse, 200, 204, 205
La Plata, 26
La Plata Island, 26
La Sola Island, 334, 345
La Viuda, 31
Labatlan, 429
Lacépède Islands, 270–272, 470
Laclede County, Missouri, 403
Lady Elliot Islet, 256, 257
Lady Musgrave Islet, 257
Lagarto, 44
Lake Lahontan, 133, 464
Lake of Maracaibo, 384
Lake Valencia, 384
Lake Wheelhamby, 275, 477, 478
Lakemba Island, Fiji, 187
Lama vicuña, 112
Lambert Bay, 144, 151, 152

- Lambert Bay Island, 151
 lamellibranchs, 351
 Lampasas County, Texas, 395
 Lamprechtskogelhöhle, 438
 Langebaan, 144, 157, 376, 471
 Langeberg, 338
 Lang-Son, 413
 Langton Island, 267
 Lanusei, 455, 456
 Lares, Puerto Rico, 381, 385–387
 Laridae, 366
Larosterna inca, 21, 30, 51, 61, 62
 Larrañaga Island, 28
Larus, 60
 atricilla, 327
 belcheri, 18
 dominicanus, 18, 142
 heermanni, 125, 129, 130
 modestus, 18, 60, 105
 novae-hollandiae, 256
 occidentalis, 131
 occidentalis livens, 125
 occidentalis wymani, 125
 pacificus, 266
 Larut, 415
 Las Cruces, New Mexico, 398, 399
 Las Hormigas de Afuera, 32
 Las Marias, 385, 387
 Las Piedras, 463
 Las Tetras, Mejillones, 113, 114
 Las Tres Marias Islands, Gulf of California, 125, 133, 196, 367
 Las Tres Marias Islands, off Pisco Bay, 44
 Las Vegas, Nevada, 401
 Las Vegas, Vera Cruz, 395
 Last Hope Inlet, 382
 L'Atalaye, 388
 Latei Tonga, Fiji, 187
 Latei Viti, Fiji, 187
 laterite, 158, 348, 349
 Latham Island, 291, 303–305, 362, 364, 367, 368
 Lauderdale County, Alabama, 402
 Laura Bay Point, 269
 Lautaro, 106
 Lava, New Mexico, 398, 399
 Laval, 446
 Lawrence Rocks, 265
 Laysan albatross, 186
 Laysan Island, 198, 200, 201, 205–207, 366, 368, 371, 372
 Laysan rail, 201
 Laysan teal, 201
 Lazareff Island, 212
 Lazareva pécina, 426
 Le Leizour Island, 258
 lead, 448, 449, 480
 Leasburg Cave, Missouri, 403
 L'Echequier Islands, 226
 lecontite, 384, 422, 463, 481
 Left Imperial Cave, New South Wales, 408, 409
 Leon, 451
 Lepidoptera, 406
Lepturus, 179
 repens, 172, 182, 184, 186
 Lerida, 451, 452
 Lesser Antilles, 315, 327, 329, 333
 Lesueur Island, 271
 Lettenmayerhöhle, 439, 440
 leucophosphorite, 275, 477, 478
 Lewis Island, 268
 lewistonite, 337
 lichens, 202–204, 220, 369, 370
 Lideron Island, 189
 Liderous Island, 189
 Liguanea Islands, 268
 Lijang na Moewap, 413
 L'Ilot du Commandeur, 348
 Lima, 46
 Limbé Island, 284
 limes, 212
 limestone, 202, 209, 211, 212, 216, 222, 226–228, 230, 235, 236, 238–240, 246–252, 265, 268, 269, 273, 274, 285–291, 299–302, 314, 318, 320, 323–326, 328–330, 338–345, 347, 376–378, 385, 389, 392–397, 401–403, 405, 408–412, 414–416, 418–421, 423, 426–429, 431–433, 435, 437, 443, 444, 447–449, 451, 457, 461, 463, 465, 473, 474
 belemniferous, 33
 coral, 173
 Dorcasia, 153, 156
 shelly, 33, 34, 153, 265, 269
 Limon, 385
 Line Islands, 160, 163, 165, 167, 183, 186, 188, 192–195, 200, 208, 223, 251, 280, 368, 370, 371, 373–375, 379
 Lion Rock, Tinian, 235
 lions, 418
 Lisiansky Island, 198, 200, 207
 lithothamnium, 191, 192, 273, 286, 298
 Little Borenore, 409
 Little Cayman Island, 320
 Little Curaçao, 338, 345, 363
 Little Ganges Island, 189
 Little Hanish Island, 307
 Little Highrock Canyon, Nevada, 401
 Little Scrub Island, 328, 331, 344
 Little Swan Island, 319
 lizards, 19, 197, 347
 Llano County, Texas, 395
 Llimiana, 452
 Loa basin, 112
 Loa River, 106
 Loaita Island, 283
 Lobos, Punta Gruesa, 98

- Lobos de Afuera, 22, 28, 63, 72, 73, 80, 90, 93
See also Lobos Islands
 Lobos de Tierra, 15, 21–23, 26–29, 36, 52, 54, 63, 66, 70, 74, 76, 80, 90, 296
See also Lobos Islands
 Lobos Islands, 9, 21, 31, 48, 51, 53, 56, 68, 88, 89, 121, 367, 481
 lobster, 153
 Lomitas, 22
 Long Island, Chesterfields, 257
 Long Island, Northern Islands
See North Long and South Long Islands
 Longwood, St. Helena, 314
 Lord Howe Island, 256
 Lord North Island, 232
 Los Archipelago, 158, table 54
 Los Coronados Islands, 127
 Los Frailes, 325
 Los Frayles, 334, 345
 Los Hermanos, 317, 318, 334, 345
 Los Leones, 29
 Los Monges, 342–345, 465, 466
 Los Monges del Norte, 342
 Los Monges del Sur, 342
 Los Morros de San Juan, 384
 Los Roques, 333, 336, 345
 Los Testigos, 333, 334
 Lost Cove Cave, Tennessee, 404
 Lot, 425, 444, 449
 Louisiana, 394
 Louth Bay, 268
 Louth Island, 268
 Lovelock, Nevada, 133, 464
 Low Cay, Bajo Nuevo, 321
 Low Island, 189
 Lower California, 122–133, 310, 475
Loxodonta (Palaeoloxodon), 249, 252
 Lubbock County, Texas, 397
 Lucas Cave, New South Wales, 409
 Luderitz Bay, 143, 146
See also Angra Pequena Bay
 Ludovic Island, 147
 Lula, 456
 Lunaguara Valley, 49
 Lunkany Valley, 428
 Lunz, 439
 Lusby Island, 267
 Lutke, 227
 Luzon, 412, 413
 Lyngbya, 197
aestuarii, 197
lagerheimii, 197
versicolor, 197
 Macabí Islands, 15, 20–23, 29, 30, 48, 56, 66, 69, 81–83, 95, 481
Machirhamphus alcinus, 411
 McKean Island, 177–180, 189, 193, 321
 Mackin Island, 189
 Maclear Deep, 285
Macronectes gigantea, 262, 263
Macrotus waterhousii waterhousii, 389
 Madagascar, 288, 292, 299, 300, 302, 421
 Madang District, 410
 Madeira, 158
 madrepores, 210, 280, 281, 332
 Madrid, 451
 Magallanes, 353
 Magdalena Bay, 123–126, 129
 magnesia, 73, *passim*
 magnesium, 85, *passim*
 magnesium ammonium phosphate, 153, *passim*
 magnesium borophosphate, 117, 119, 475
 magnesium carbonate, 210, *passim*
 magnesium hydrogen phosphate, 118, *passim*
 magnesium phosphate, 89, *passim*
 magnetite, 274, 329
 Magur, 227
 Mahe, 294
 Mahogany Hall Cave, 391
 Main Island, Aldabra, 297
 Maine, 394
 Mait Island, 303–305, 360, 367
 Makaraku Island, 232
 Makatea, 208–212, 252, 299, 340, 363, 376–378, 469, 471, 472, 474, 482
 Makin Island, 189
 Makunouti, Kita Daito Jima, 237, 238, 240
 Málaga, 451, 452
 Malaga, New Mexico, 398
 malagas, 140–142, 144
 Malagas Island, 140, 141, 144, 151, 152
 Malay States, 414
 Malden Island, 89, 163–167, 174–177, 181, 184, 190, 191, 193, 213, 259, 364, 368, 379, 465
 Mallophaga, 19
 Mallorca, Mediterranean Sea, 452
 Mallorca, Peru, 32
 Malpelo Island, 120–122, 475, 476, table 54
 Mammoth Cave, Kentucky, 405
 Mamre, 157
 Manacor, 452
 Manapwani Cave, 420
 Manati, 385
Manatus, 338, 342
 manganapatite, 468
 manganese dioxide, 286
 mangroves, 273, 280, 282, 336, 349
 Manihiki, 175, 189, 190
 man-o'-war birds, 166
 Mansa, 44
 Manu Island, 226, 374
 Manua, Samoa, 189
 Manua group, 191
 Maracaibo, 333, 384
 maraes, 175

- Maraki, 189
 Maranhão, 346, 348
 Marble Cave, Missouri, 402
 Marche, 456
 Marcus Island, Pacific Ocean, 227, 235, 236, 250, 251, 366
 Marcus Island, Saldanha Bay, 151, 152
 Margarita Island, Peru, 44
 Margarita Island, Venezuelan Leewards, 333, 334
 María Cleofa Islands, 125, 133
 Maria Island, 126, 129
 Maria Magdalena Island, 133
 Maria Rock, 128, 129
 Mariana Islands, 223, 227, 233, 250, 252, 377, 405, 475
 Marie Louise Island, 291, 295
 Maries County, Missouri, 403
 Marinduque Island, 413
 Marion County, Arkansas, 405
 Marion County, Tennessee, 404
 marl, 408, 409
 Marlborough, 410
 Maro and Dowsett Reef, 205
 Maro Reef, 205
 Marotiri, 188
 Marpi, Saipan, 234
 Marpo, Tinian, 235
 Marquesas Archipelago, 160, 181, 182, 321
 Marraõ, 451
 Marshall Islands, 223, 227, 228, 250
 marsupials, 409
 Marte di Malo, 456
 Martin Vas Islands, 313
 Martinique, 328, 329, table 54
 martinite, 331, 340, 341, 344, 464–467
 Marum Island, 267, 268
 Marvel Cave, Missouri, 402, 403
 Mary Anne Passage, 271
 Mary Letitia Island, 189
 Marzoque, 32
 mascagnite, 91, 92, 94, 463
 Mascarene Islands, 292, 421
 masked boobies, 186, 305
 Mason County, Texas, 395
 Massat, 445
 Massawa, 306, 307
 Massawa Channel, 307, 308
 Masthead Islet, 257
 Matahiva, 208, 212, 376
 Matanza, 391
 Matau-a-Maui, 261
 Matelles, 446
 Mathildengrotte, 438
 Mathurin Bay, 293
 Matthew Island, 189
 Matto Grosso, 382
 Maty Island, 226
 Mauke, 208
 Mauki, 208
 Mauritius, 257, 292–294, 302
 Mauti, 208
 Mayaguez, 385
 Mayenne, 444
 Mayersdorf, 439
 Mazorca Island, 21, 31, 56, 58
 Mbeya Peak, 419
 Medina County, Texas, 395
 Medinilla, 235, 250
Megaderma frons, 420
Megalonyx jeffersonii, 404
Megalopterus, 201
 Méjeannes-le-Clap, 446
 Mejillones Peninsula, 47, 48, 65, 72, 89, 93, 96, 106, 113–120, 361–365, 474, 475, 477
 Melbourne, Australia, 256
 Menai, 292, 297
 Mercury Island, 140, 146, 147
 Merkensteinerhöhle, 439
 Merman Island, 147
 mesembreanthemum, 172, 175
Mesembryanthemum, 265
 mesembryanthemum, 174
 Mesia Islands, 31
 Mesilla Park, New Mexico, 398
 mesquite, 393
 metabrushite, 331, 449, 465
 metavariscite, 122, 475
 Metazoa, 77
 Meuw Island, 151
 Mexico, 393, 395
 Mexican free-tailed bat, 393
 mica, 436
Micranous hawaiiensis, 201
leucocapillus, 213
 Microchiroptera, 381, 420
Micrococcus ureae, 78
 middens associated with guano, 46, 97, 98
 Middle Cay, Pedro group, 317, 322
 Middle Cay, Serranilla Cays, 321
 Middle Island, Lacépède Islands, 272
 Middle Island, Nightingale group, 353
 Middelburg District, Transvaal, 477
 Midway Island, 198, 200, 201, 207
 Millard County, Utah, 402
 Miller County, Missouri, 403
 Milne Island, 267
 Mina Caridad, 413
 Minadanao Island, Sumatra, 413
 Minami Daito Jima, 223, 237
 Minas Gerais, 382
 Minatoguchi, Kita Daito Jima, 239
 Mindoro, 413
 Minerve, 447
 minervite, 261, 275, 409, 421, 423, 448, 449, 467, 478–480, 482

- Miniopterus*, 424, 444, 448
schreibersii, 422, 424, 426, 428, 445, 446
Miogypsina polymorpha, 238
Miogypsinella borodiniensis, 238
Mios Kairu, 226
Mirelles, 382
misenite, 94
Miskito Bank, 319
Misserghin, 423, 479
Mississippi, 394
Missouri, 394, 396, 402, 403
mites, 112, 420
Mixnitz, 381, 424, 431, 462, 472, 473, 480
See also Drachenhöhle
Miyako Jima, 247, 249, 251, 252, 377, 378
moaning birds, 186
Moca, 385
Mochica finds, under guano, 69, 70
Modu Manu, 202
Mohabbakah Islands, 307
Moku Manu, 202
Mole Island, Purdy group, 223, 226
Molina's pelican, 20
Moline de Zaragoza, 391
Mollendo, 21, 44
mollusks, 139, 153, 156, 210–212, 238, 247, 278, 298, 313, 338, 341, 342, 351, 411
Molong, New South Wales, 409
Molossus fortis, 385
Mombasa, 420
Mona Channel, 317
Mona Island, 317, 322, 326, 327, 344, 393
monetite, 80, 126, 130–132, 173, 181, 306, 310, 313, 327, 332, 334, 343, 344, 391, 449, 464–466
Money Island, 282
Monge del Este, 342
Mongon, 31
Mongoncillo, 31
monite, 327, 343
Monito, 322, 326, 327, 344, 345, 465
Monk's Island, 343
Monophyllus frater, 385
portoricensis, 385
Monos Island, off Trinidad, 327
Monroe County, Indiana, 403
Monroe County, West Virginia, 405
Monroig, 452
Montalban, Luzon, 412, 413
Monte Alburno, 456, 479
Monte Luboe, 413
Monte Rorigo, 382
Montebello Islands, 270, 272
Montemaggiore, 453
Monterrey, 395
Montevideo, 382
Montgomery County, Missouri, 403
Montrond, 446
Moolooloo Run, 409, 410
Morant Cays, 318, 344
Morant Keys, 323
Moravia, 443
Moravica, 427
Morelos, 395
Morillo, 98
Mormoops megalophylla, 395
morning glories, 205
Morocco, 424
Moromaho, 284
Morosoglio, 452
Morovis, 385
Morrison Rocks, 247
Morro, Pabellón de Pica, 102, 103
Morro de Copiapó, 48
Morro de Mejillones, 113–116
Morro de Punta Moreno, 333
Morro de Sama, 22
Morro de Tarapacá, 98
Morro Moreno, 113
Morro Solar, 22
Morus capensis, 140, 141, 151, 153
serrator, 265
serrator rex, 5, 261
serrator serrator, 264, 266
Moruya Caves, 409
mosquitoes, malarial, 394
mosses, 220, 226, 369
Mother Carey's chicken, 62
moths, 394
tineid, 420
Motu Iti, Hergest Rocks, 181
Mt. Ankonokono, 421
Mount Chappell Island, 265
Mt. Marpi, Saipan, 234
Mt. Nagyszal, 429
Mt. Sobis, Borneo, 410
Mount Widderin, 406
mountain sheep, 401
mouse, 457
long-tailed field, 433
Mouse Island, Purdy Islands, 223, 225, 226
Mozambique Channel, 288, 299, 301, 302, 364, 419
Muav cave, Grand Canyon, 401
mudstones, 266
muellerite, 407
Muertos Island, 327
Muggendorf, 444
Mugil cephalus, 21
mullet, 21, 211
Mulmein, 418
mummified penguin, 30
mummy, of man, beneath guano, 148
Munida, 19
Mur, 437
Murcia, 451
Murtal, 437
mushrooms, 229

- mutton birds, 62, 166, 175, 181, 255, 261–263, 265–268
 Muzqiz, 395
 myersite, 204, 476, table 54
Myliobatis, 338
Myotis, 434, 444, 451
 bechsteinii, 433, 444
 daubentoni, 423, 444
 exilis, 444
 griseus, 394, 402, 404
 gryphus, 404
 keenii septentrionalis, 404
 kormosi, 444
 lucifugus lucifugus, 394, 402
 mixniliensis, 434
 myotis, 422–424, 426, 428, 429, 434, 443, 445, 446, 450, 451, 457
 mystacinus, 423, 434
 nattereri, 423, 433
 oxygnathus, 424, 445, 446, 451, 452
 sodalis, 394, 402, 403
 velifer, 395
 myriapods, 293
 Myxophyceae, 197

Najas marina, 197
 Nike Islet, Caroline Island, 187
 Nam Yit Island, 283
Nama sandwicensis var. *laysanicum*, 207
 Naolinco, 395
 Nassau Island, 190, 191
Natalus mexicanus, 395
 stramineus, 395
 Nativity Islands, 126, 128, 129
 Nauru Island, 160, 171, 177, 208, 210, 212–214, 216–222, 226, 252, 287, 299, 303, 339, 340, 363, 376–380, 469–474, 482
 nauruite, 216, 221, 299, 469, 470, 472
 Navarra, 451
 Navassa, 322–325, 344, 345, 362, 363, 376–378, 465, 475, 482
 Necker Island, 198, 200, 203, 307, 476, table 54, 477, 480
 neolithic hearth, 433
Neotoma, 405
 fuscipes streator, 401
 magister, 404
Nephrolepidina, 227
 tournoueri, 238
 Neptune Island, 268
Nesofregatta albigularis, 166
Nesophontes, 388
 edithae, 385
 micrus, 389
Nesophylax ater, 212
 Netherlands
 See Holland
 Nevada, 400, 401, 464

 Nevil Island, 232
 New Caledonia, 253, 258
 New Guinea, 163, 222, 223, 276, 410
 New Ireland, 410
 New Island, Falklands, 357
 New Mexico, 395–399, 464
 New Plymouth, 260
 New South Wales, 408, 409, 480
 New Zealand, 5, 177, 253, 260, 366, 370, 410, 478, 482
 newberyite, 118, 119, 313, 406–408, 422, 474, 482
 Newton County, Arkansas, 405
 Ngatik, 228, 250, 251, 373, 374
 Niah River, 410
 Niau Island, 208, 211, 212, 376
 Nickajack Cave, Tennessee, 394, 404
 nickel, 275
 Nightingale Island, 353
 Nihoa Island, 198, 200–204, 370
 Niuhau, 202
 Ninghamboun Hills, 275
 Ninigo group, 223, 226, 250, 251, 374
 niter, 133, 382, 384, 397, 399, 401–404, 413, 464
 nitrate, 27, *passim*
 nitratite, 133, 399, 401, 464
 nitrocalcite, 383, 401, 413, 464
 nitrogen, 18, *passim*
 relation of, to phosphorus in guano, 78 *et seq.*
 nitrogen compounds in guano, 75 *et seq.*
 Niue Island, 208
 Nixloch, 439
Noctilio, 327, 381, 393
 leporinus mastivus, 385
Noctiluca, 139
 noddies, 165, 186, 197, 198, 201, 236, 270, 273, 291, 308, 314, 346, 370
 noddy, brown, 326
 Red Sea, 305
 white-headed, 291
 noddy terns, 187
 Noguera Pallaresa, 452
 Noguera Ribargozana, 452
 Norah Island, 307, 308
 Norfolk Island, 256
 Normandy, 444, 446
 North Africa, cave guano, 422
 North Aldabra Island, 292
 North Bat Island, Purdy Islands, 223, 226
 North Bickers Islet, 268
 North Borodino Island, 236, 237
 North Chincha Island, 15, 20, 33–35, 40, 41, 43, 60, 61, 63, 68, 69, 74, 80, 81, 194, 379
 See also Chincha Islands
 North Danger Reef, 283
 North Equatorial Current, 5, 7, 160, 304, 317
 North Island, African Banks, 291
 North Island, Agalega Islands, 294
 North Island, Macabí, 29, 30

- North Island, New Zealand, 260, 282
 North Keys, Serrana Cays, 321
 North Long Island, 146
 North Pacific Current, 198
 North Pigeon Island, 273
 North Reef, 280
 North Rocks, Serrana Cays, 321
 Northeast Cay, North Danger Reef, 283
 North-East Islands, Cosmoledo, 297
 Northeast Islet, St. Paul's Rocks, 346
 Northeast Key, Orchilla, 334
 Northeast Quoin Island, 307, 308
 Northeast Trade Wind, 13
 Northern Islands, 135-137, 140, 143-149, 152, 362
 North-West Island, Aldabra, 292
 North-West Island, Capricorn group, 255, 257
 Norway rat, 169
 Norzagary, 413
 Nosi Anambo, 299, 300, 302
 Nosi Andrahombava, 301
 Nosi Andrano, 300
 Nosi Andriangori, 301
 Nosi Andriangosy, 301
 Nosi Andrianmitariko, 301
 Nosi Ankarana, 421
 Nosi Banjoana, 421
 Nosi Bemoka, 301
 Nosi Bory, 301
 Nosi Fasi, 301
 Nosi Hao, 301
 Nosi Lava, Barren Islands, 300
 Nosi Lava, off Madagascar, 300
 Nosi Maroantaly, 300
 Nosi Ratafani, 301
 Nosi Trozona, 300
 Nosi Very-very, 301
 Notch, Missouri, 403
Nothrotherium, 382, 401
 shastense, 398, 401
 Novaya Zemlya, 361, 369
 Nuevo Leon, 395
 Nukahiva, 181
 Nukunono, 189, 190
Nyctalus sicalus, 450
Nycteris hispida, 420
Nyctinomus, 410, 450
 limbatus, 420
 plicatus, 411
 teniotis, 450
 Oahu, 198
 Oberholzer Station, 418
 Ocean Island, Hawaiian Leewards, 198, 207
 Ocean Island, Pacific Ocean, 160, 177, 208, 210,
 213-219, 221, 222, 231, 252, 287, 299, 303,
 339, 340, 363, 376-378, 469-473, 482
Oceanodroma castro, 313
 castro castro, 158
 fuliginosa, 202
 hornbyi, 112, 113
 markhami, 112
 markhami owstoni, 202, 206
 markhami tristami, 202, 203, 206
 melania melania, 128
 monorhinus socorroensis, 128
Ochrosia oppositifolia, 186
 Ochsenloch, 438
 Ocona, 22
Oedogonium, 197
 Oestcher, 439
Oestralata parvirostris, 166
 Ō-ike Lake, Kita Daito Jima, 237
 oil bird, 384
 Oil Islands, 293
 Ojcow, Poland, 443
 Okinawa, 248
 Okino Daito Jima, 236, 246, 251, 252, 363, 376-
 378
 Old Loiza, 385
 Old Providence Island, 318, 344
Olearia, 262
 Olien, 454, 455
 Olifants River, 151
 Olive Island, 269
 olivine, 346, 421
 Olonzac, 447
 Olosenga, 190
 One Tree Islet, 257
 Onetana, 410
 Onna-Mura, Yamada, Okinawa, 248
Oocystis solitaria f. *major*, 197
 ooguanolite, 94
 opal, 329, 422
Opisthonema libertate, 124
 opossum, 458
Opuntia caribaea, 336
 elator, 336
 Oradia Mare, 428
 Oran, 422, 423, 466, 467, 479
 oranges, 212
 Orchilla, 333, 334, 345, 363, 376
 Oregon, 393, 394, 402
 Oregon Cave, Missouri, 403
 Oregon County, Missouri, 403
 Orinoco, 345
 ornithite, 465
Ornithodoros amblus, 19
 Orosei, 454, 455
 Oscura, Cabachuelas, Morovis, 385
 Oshima, 248
Ostrea, 33
Otaria byronia, 18, 72
 jubata, 72
 Oude Post, 155
 Oued Berdi, 422
 Oulad ben Dahmane, 422

- Oviedo, 451
 Ovillos, 22
 owls, 389, 433, 457, 458
 oxalate, 71, *passim*
 oxalic acid, 72, 77, *passim*
 oxamic acid, 77
 oxammite, 61, 77, 80, 91, 92, 94, 119, 462, 463, 481
 oxen, 418, 457
 oxycalcite, 92
 oxygen, 124, *passim*
Oxyrhina cf. *glauca*, 338
 gomphodon, 338
 oyster opener, 62
 oysters, 281
 Ozark County, Missouri, 403
 Ozsowa, 443
- Pabellón de Pica, 36, 51, 70, 95, 96, 101, 102, 107–109, 118, 477
 Pacay Cove, 45
 Pachacamac Islands, 21–23, 32, 52, 56, 74, 75
 Pachino, 456
Pachyptila turtur, 265
 Pacific Ocean, 5, *passim*
 Pacific rat, 169
 pack rats, 401, 404
 Padalarang, 412
 Padang Lawas, 413
 Padang Rengas, 415
 Pahang, 416
 Paitone, 456
Palaeoloxodon namadicus, 249
 Palau Islands, 223, 227, 230, 232, 475
 Palawan, 282
 paleolithic remains, 433, 458
 Palestro, 422
 Palm Island, 282
 palmerite, 261, 457, 478, 479, 482
 palms, 196, 202, 205, 210, 279, 280, 283, 310, 323
 Palmyra, 163, 165–167, 183, 185, 190, 192, 194–196, 364, 370, 373–375
 Palominos Rocks, 21, 22
 Pampa del Toco, 112, 113, 462
 Pampa del Toco Desert, 112
 Pan de Azúcar, 48
 Panaderu, Saipan, 234
 Panama, Isthmus of, 13
 Panay, 413
Pandanus, 166, 184, 185, 187, 226, 370
 rockii, 185, 186
 Panguia Island, 356
 Panna Island, 233, 250, 374
 Panopa, 214
 Papala Islet, Palmyra, 186
 Papeete, Tahiti, 188
 Paquica, 106
 Para, 346
 Paracas, 43
 Paracel Reefs, 276, 278–280, 376
 Parapara, 384
 Paratoo Siding, 274, 477, 478
 paratooite, 274
 Parawan, Utah, 402
 parrots, 167, 184
 Partido de Inde, 395
 Partney Island, 267
 Pashiiru Island, 285
 Paso del Toro, 395
 Patache, 100, 109, 110
 Patagonia, 93, 95, 353, 357–359, 363, 366, 382, 467, 474, 478, 482
 Paternoster Island, 136, 151, 152
 Patillos, 99, 100, 109, 110
 Patillos Island, 45, 47, 100
 Patos Island, 124, 129, 130
 Patsy's Springs, 410
 Pattle Island, 280
 Paumotu group
 See Tuamotu group
 Pavonia, 210
 Payta, 99
 Pearl and Hermes Reef, 198, 207
 Pearl Island, Cargados Carajos, 293
 peat, 184, 194, 195, 267
 Pecos River Valley, 397
 Pedestal Point, 147
 Pedro Bank, 321
 Pedro Cays, 322, 323, 344, 345, 367
 Pedro group, 317
 Peggau, 437, 438
 Peggauer Wand, 437
 pegmatite, 33, 269, 337, 466
 Pelado, 26
 Pelecanidae, 366
 Pelecaniformes, 5, 88, 366, 367
Pelecanoides, 36, 37, 40, 61, 62, 65, 66, 91, 94
 garnotii, 23, 37, 60–62, 93, 141, 366, 481
Pelecanus, 94
 conspicillatus, 255, 266, 273
 occidentalis, 318
 occidentalis californicus, 125–127
 occidentalis carolinensis, 318
 occidentalis fuscus, 333
 occidentalis occidentalis, 318
 occidentalis murphyi, 21, 26
 occidentalis thagus, 20, 21, 60, 64, 65, 71, 73, 90, 105
 rufescens, 141
 Peleliu Island, 231, 232, 251, 252, 376–378
 pelican, Australian, 255
 brown, 20
 Molina's, 20
 Peruvian, 20, 21, 28
 Pelican Island, Franklin Sound, 266
 Pelican Island, Houtman's Abrolhos, 273
 Pelican Island, Lower California, 124

- Pelican Island, Shark Bay, 273
 Pelican Lagoon, 267
 pelicans, 5, 20, 29–32, 51, 52, 54, 58–60, 62–65,
 71–74, 86, 90, 104, 132, 169, 265
 Pelroasa, 427
 Pelsart group, 273, 274
 Pelsart Island, 273, 274
Pemphis, 296, 298
 acidula, 296–298
 penguin, Cape, 140
 Johnny, 358
 Peruvian, 23
 Penguin Island, Lambert Bay, 151, 152
 Penguin Island, Luderitz Bay, 143, 146, 147
 Penguin Island, Saldanha Bay, 136
 Penguin Islands, Argentina, 355, 356
 penguins, 5, 30, 44, 51, 61, 62, 141, 143–146, 149,
 151, 262, 263, 265, 267, 355, 356, 358, 366,
 369, 370
 fairy, 265
 Peninsula of Paraguaná, 333
 Penne-du-Tarn, 445
Pennula, 201
 Penrhyn Island, 190
 Peña Collorada, 451
 Peñuelas, 385
 Perak, 415
 Perdu Carta, 455
 peridote, 422
 Perim, 306
 Perlis, 416, 418
Perna, 338
 Pernambuco, 382
 Persian Gulf, 308, 310
 Peru and Peruvian coast, 9, *passim*
 Peru Coastal Current, 9–11, 14, 21, 48, 120–122,
 136, 137, 481
 Peruvian pelican, 20, 21, 28
 penguin, 23
 Pescado Island, 190
 Pescadores Islands, 21–23, 32, 43, 52, 54, 55
 Peșterea dela Cheia Ampoitii, 428
 dela Ferice, 428
 dela Măgura, 427
 Petit Connétable, 348
 petrel, Hornby's, 112
 sooty, 305
 Petrel Island, 321
 petrels, 62, 113, 158, 314
 diving, 5, 23
 giant, 263, 370
 Petrosam, 428
 Petrosény, 428
 Peyrus, 445
Phaeton, 166, 333, 348, 352
 aethereus, 53, 133, 313
 aethereus aethereus, 311, 313
 indicus, 305
 lepturus, 166, 210
 lepturus ascensionis, 311
 lepturus fulvus, 286
 rubricauda, 131, 166, 186, 201, 203, 206, 207
 rubricauda westralis, 286
 Phalacrocoracidae, 366
Phalacrocorax, 59, 275, 366
 a. africanus, 140
 albigula, 60
 auritus, 18
 auritus albociliatus, 125, 127, 129, 367, 370
 bougainvillei, 14, 15, 19, 29, 30, 32, 47, 48, 51,
 59, 60, 63–66, 73, 87, 104, 141, 366, 367, 369,
 481, 482
 capensis, 140, 141, 143, 145
 carbo lucidus, 140, 141
 carbo sinensis, 370
 fuscescens, 265, 266
 gaimardi, 30, 59, 60, 62, 64, 104, 366
 neglectus, 140
 olivaceus, 60
 olivaceus olivaceus, 30, 64
 penicillatus, 125, 127, 367
 varius, 272
Phaseolus, 272
 phenocryst, 158
 Philippine Islands, 276, 412
Phocarcos hookeri, 262
 Phoenix group, 160, 163–167, 177, 178, 180, 186,
 189–194, 200, 251, 321, 368, 370, 373, 374
 Phoenix Island, Phoenix group, 177–179, 191
 phonolite, 347
 phosphamite, 92
 Phosphate Hill, Christmas Island, 286
 phosphates, 3, *passim*
 phosphorites, 153, 154, 226, 409, 413, 449, 471, 475
 phosphorus, 18, *passim*
 relation of, to nitrogen in guano, 78 *et seq.*
 phosphorus economy of the earth, guano deposi-
 tion in, 360
 phosphosiderite, 122
Phyllanthus niruri, 196
Phylloncyteris poeyi, 389
Phyllops vetus, 389
 phytoplankton, 10, 11, 123, 124, 140, 157, 373
 Picard Island, 292, 298
 Piedra Blanca, 133
 Piedra Blanca del Mar, 133
 Piedra de la Cueva, Puerto Rico, 385
 pigeons, 187, 210, 411, 422, 453, 455, 456
 Cape, 62
 pigs, 196, 411, 457
 Pilar, 413
 Pilgrim Island, 257
 Pililu Island, 231
 piloto, 352
 Pinar del Rio, 390
 Pinnacle group, 248

- pinnipeds, 262
 pintail, 167
Pipistrellus pipistrellus, 443
 pipit, 263, 369
 piqueros, 19–21, 32, 59–61, 63, 65, 66, 87, 105
 Piracaua, 349
 Pisagua, 96, 97, 107
 Pisco, 49, 67
 Pisco Bay, 9, 13, 43, 44, 48, 49, 59, 70, 110
 Pisco document, 70
Pisonia, 163, 166, 177, 183, 186, 187, 191, 192, 293, 296, 370
 grandis, 186, 191, 192
 Pitcairn, 213
 Piura, 14, 50
 plagioclase, 329, 421
 plankton, 53, 54, 58, 123, 137–139, 162, 163, 167, 237, 311, 352
Planorbis, 450
 plantains, 283
 platin, 297, 298, 301
 Playa Miller, Arica, 98
 Pleasant Island, 208
Plecotus abeli, 424, 433, 434
 auritus, 423, 433, 443
Plotus ankinga, 60
 plover, 187
 Ployte Island, Cosmoledo, 291, 292
 Plumpudding Island, 147, 149
 Po Tao, 282
Poa foliosa, 262, 370
 litorosa, 263
 Pocahontas County, West Virginia, 405
 Pocatello, 402
 pohutukawa trees, 261
 Point Abreojos, 122, 123
 Point Alacranes, 323
 Point Conception, 124
 Point San Eugenio, 128
 Point Stephens, 274
 Poivre Islands, 295
 Pokaakku, 228, 250
 Poland, 443
 Polynesian rat, 168, 212
Polypodium scolopendrum, 184
 Pomona Island, 147
 Ponape, 227–229
 Ponce, 327
 Popšička pešter, 426, 427
 porcupine, 404, 405
 Porites, 210
 porphyry, 104, 154, 155, 355, 476, table 54, 477
 Port Alexander, 134
 Port Curtis, 274
 Port Lincoln, 268
 Port Nolloth, 136
 Port-au-Prince, 388
 Portland, Australia, 406
 Portland, Oregon, 402
 Porto Cristo, 452
 Porto San Bartolome, 128
 Portugal, 451
Portulaca, 168, 170, 172, 175, 179, 205, 207, 271
 lutea, 168, 170, 172, 203–205
Porzanula, 201
 palmeri, 201, 206
 Possession Island, 140–142, 146, 147, 151
 potassium, 85, *passim*
 potassium ammonium sulphate, 91, *passim*
 potassium oxide, 73, 85, *passim*
 potassium phosphate, 150
 potassium sulphate, 463
 Potchefstroom, 418, 419
 Potgietersrus District, Transvaal, 477
 Potosi Rocks, 133
 potoyuncos, 23, 44, 60, 62, 63, 66
 Pratas Island, 276, 278
 Pratas Reef, 278
 Presidio County, Texas, 397
 Priesnitz Cave, 429
 prion, fairy, 265
Prion ariel, 265
 prions, 62
Pritchardia, 205
 remota, 202
Procapra, 420
 Procellariiformes, 5, 366
Procelsterna, 120
 albitrissa, 120
 cerulea, 165, 212, 370
 cerulea imitatrix, 120
 cerulea nebulosa, 165
 cerulea saxatilis, 200, 202, 203, 205
 proctotrupid, 420
Prosopis glandulosa, 393
 Prosperous Bay, St. Helena, 314, 315
 Prosperous Hill Bay, 314
 Providence Island, 288, 291, 302
 Providence Reef, 296
 Provo, 402
 Prszenie Cave, 429
 pseudokeratin, 462
Pseudomonas, 78
 aeruginosa, 77
 fluorescens, 77
 non-liquifaciens, 77
 pseudomorphs of birds' eggs, 91, 93, 119, 463, 481
 pseudoscorpions, 112
 pseudostalactites, 204
 pseudostalagmite, 411
Pseumatophorus japonicus diego, 124
Pterodroma alba cantonia, 166
 cooki defilippiana, 120
 leucoptera hypoleuca, 200, 201
 neglecta, 120
Pteronotus davyi fulvus, 395

- Ptilinopus purpuratus calcurus*, 210
purpuratus coralensis, 210
insularis, 212
 Pueblo, 393
 Puerto Deseado, 356
 Puerto Ingles, 100
 Puerto Rico, 317, 322, 327, 344, 381, 385–389, 393, 480
Puffinuria, 62
urinatrix, 62
Puffinus, 89, 175, 212, 314
assimilis bailloni, 291, 294
assimilis tunneyi, 273
griseus, 54, 112, 262, 263
hypoleuca, 206
lherminieri dichrous, 166
nativitatis, 166, 201–203, 205, 206
opisthomelas, 125, 128, 393
pacificus cuneatus, 186, 201–203, 206, 207
pacificus chlororhynchus, 166, 291, 294
tenuirostris, 265, 266
tenuirostris tenuirostris, 255
 Pujal, 395
 Pukapuka, 190
 Pulaski County, Missouri, 403
 Pulo Manuk, 284
 Pulu Batu, 285
 Pulu Seraya Ketjil, 285
 pumice, 236, 241, 245, 246, 301, 377, table 54
 Punguluma, 419
 Punta Abalos, Pinar del Rio, 322
 Punta Arenas, 106
 Punta Bermejo y Patillo, 22
 Punta Blanca, 105
 Punta Chancay Grita Lobos, 22
 Punta Chomache, 47, 104
 Punta Colorada, 26
 Punta Corcovada, 26
 Punta de Chilca, 22
 Punta de Coles, 22
 Punta de Lobos, 70, 96, 103, 104, 107, 108
 Punta de Paquiza, 106
 Punta Falsa de Chipana, 105, 106
 See also Chipana
 Punta Grande, 98
 Punta Gruesa, 98, 99, 110
 Punta Islay, 23
 Punta Lomas, 22
 Punta Olleros, 22
 Punta Pichalo, 97, 109
 Punta San Nicolas, 22
 Punta Solar, 32
 Punto Loberia, 72
Pupa, 330
Pupoidopsis hawaiiensis, 184
 Pupug, 412
 Puru Island, 233, 250, 374
 Purdy group, 223, 225–227, 250, 251, 374, 375
 purines, 74, 77, *passim*
 Putiare, Makatea, 209
Pygoscelis papua, 358
 Pyramid Rock, 265
 Pyrenees, 424, 425
 See also Basses Pyrénées, French Pyrenees, Hautes Pyrénées, Pyrénées Orientales, Spanish Pyrenees
 Pyrénées Orientales, 445
 pyrite, 325, 349, 478
 pyroclastic, 343, 344
 pyroguanite, 343
 pyrophosphorite, 466
Quadrivisio bengalensis, 420
 Quartermaster Island, 357
 quartz, 122, 154, 158, 273, 306, 337, 341, 350, 351, 355, 382, 428, 431, 432, 436, 476
 quartzites, 28, 274
 Quebrada de las Torres, 48
 Queen Place Claim, Nevada, 133
 Queen Post Office, New Mexico, 399
 Quiani, 98
 Quilca Islets, 22
 Quillos, 44
 Quingey, 446
 Quiros Island, 190
 Quita Sueño, 320, 321
 Quito Sereno, 320
 Quito Serrano, 321
 Quoin Bluff, Shark Bay, 273
 Quoin Point, 152
 Raab, 429
 Rabbit Island, Louth Bay, 268
 Rabbit Island, Port Lincoln, 268
 rabbits, 201, 205, 207, 371, 457
 rail, flightless, 212, 311
 Laysan, 201
 Railroad Valley, Nevada, 401
 rails, 186, 207
 Raine Island, 253, 255, 256
 Raivavae, 175
 Rakahanga, 189, 190
 Rallidae, 201
 Rampart cave, Grand Canyon, 401
 Rancho la Brea, 398
 Rangiroa, 212
 Rantau, 412
 Rapa, 188
 Rasa Island, Gulf of California, 130
 Rasa Island, Pacific Ocean, 236, 246
 Raščici, 427
 rat, Norway, 169
 Pacific, 169
 Polynesian, 168, 212
 Rat Island, Houtman's Abrolhos, 273
 Rat Island, Purdy group, 223

- Rata Island, 345, 347
 rats, 165, 168, 177, 201, 306, 389, 410
 See also rodents
 brown, 169
 pack, 401, 404
Rattus rattus exulans, 165
 Ravin de Misserghin, 423
 ray, 338
 Raza Island, Gulf of California, 124–126, 130, 131, 362, 465
 Recherche Archipelago, 267, 269
 red deer, 457
 Red Sea, 124, 306, 307, 310, 362, 365
 Red Sea noddy, 305
 Red Sea sooty tern, 305
 red-billed tropic bird, 314
 red-footed boobies, 168, 292
 Redonda, 159, 328, 329, 331, 344, 345, 352, 362, 376, 475, 476, table 54, 477, 478
 redondite, 159, 275, 328, 329, 421, 475, table 54, 477, 478
 red-tailed boatswain's bird, 186
 red-tailed tropic bird, 166
 Reeves County, Texas, 397
 Reevesby Island, 267
 Reid Reef, Fiji, 188
 Reirson Island, 189, 190
 Remier Island, 290
 Repolusthöhle, 438
 reptiles, 4, 210
 Réunion, 384, 421, 463, 474, 479, 480
 Revillagigedo Islands, 367
 Rhenish Hessen, 444
Rhinolophus, 422, 423, 444, 451
 ferrum-equinum, 423, 429, 444, 446, 457–459
 hipposideros, 381, 424
Rhipidura, 214
 Rhône, 444
 rhyolite, 397, 401, 402
 Riam Kanan, 412
 Right Imperial Cave, New South Wales, 409
 right whale, 260
 Rimitara, 167
 Rinconada, Pabellón de Pica, 102, 108
 Rinconada, Punta Falsa de Chipana, 106
 Rio Bembaroque, 134
 Rio Caribe, 333
 Rio de Janeiro, 352
 Rio dos Mortes, 382
 Río Guayas, 53
 Río Loa Valley, 112
 Rio Negro, 355
 ripio, 116, 119, 131
 Riu Kiu group, 223, 236, 247, 248, 250–252, 366, 376, 475
 Riverside County, California, 401
 Rivoli Bay, 410
 Rizal, 413
 Roast Beef Island, 147
 Rob Roy Mine, Utah, 402
 Robben Island, 136
 Robe, 267
 Robert Island, 280
 Rocha de Pinda, 134
 Rocheport Cave, 394, 402
 rock doves, wild, 411
 rock hopper, 358
 Rocky Island, Coffin Bay, 268
 Rocky Island, Gulf of Carpenteria, 255
 Rocky Island, Paracel Reefs, 278, 280
 Rocky Point, Gulf of California, 128
 rodents, 112, 381, 389, 404, 411, 439
 See also rats
 Rodeo, New Mexico, 399
 Rodlerhöhle, 439
 Rodriguez Island, 288, 292
 Rötelloch, 439
 Rogersville, Alabama, 394, 402
 Rogewein Island, 190
 Rokely Island, 268
 Roncador Cay, 320, 321
 Ronda, 452
 Rose Atoll, 166, 167, 191, 192, 194, 365, 370, 371
 Rose Islet, Rose Atoll, 191, 192
 Roswell, New Mexico, 398
 Rota Island, 233, 234, 251, 252, 376–378, 405
Rotalia, 226
 Roti Island, 285
 Round Island, 151
 rubidium, 448, 480
 Rumania, 424, 427, 428, 443
 Russey, 446
 Russia, 461
Rynchops nigra, 28, 60, 105
 Sa Xemesa, 455
 Sacco de Baleia, 134
 Sacramento, 98
 Sadie Islands, 271
 Saigon, 276
 St. Brandan's Islands, 288, 293, 373
 St. Catherine, Jamaica, 391
 Saint Chapte, 447
 St. Christopher Island, 299
 St. Croix Island, 134
 St. Eustatius Island, 332
 Saint Gilles Ravine, 421
 St. Helena, 311, 313–315
 St. Helena Bay, 136, 152
 St. Joseph Island, 291
 Saint Martin d'Ardèche, 447
 St. Martins Island, 328, 331, 344
 St. Michel, 388
 St. Paul's Rocks, 29, 121, 345–347
 St. Pierre Island, 288, 292, 296, 302
 St. Thomas, 332

- St. Thomas, Jamaica, 391
Saint-Ambroix, 446
Saint-Denis, 422
Sainte Croix de Volvestre, 447
Sainte-Anastasie, 447
Saipan, 234, 235, 251, 252, 376-378, 405
Sakishima group, 249
Sala, 456
salammoniac, 28, 93
Salaverry, 21, 53
Saldanha Bay, 136, 139-141, 151-156, 364, 376, 378, 474-476, table 54, 477
Salerno, 456
Salinas, 112, 113
Salisbury Island, 269
salitre, 27
Sallèles-Carbardès, 447
salt, 80, 81, 85, 97, 105-107, 113, 117, 134, 150, 169, 172, 180, 181, 197, 273, 307, 406, 473
Salton, California, 401
saltpeter, 105, 382, 394, 396, 403, 413, 464
Saltpeter Cave, Clay County, Tennessee, 404
Saltpeter Cave, Crawford County, Indiana, 403
Saltpeter Cave, Marion County, Tennessee, 404
Saltpeter Cave, Monroe County, Indiana, 403
Saltpetre Cave, Rogersville, Alabama, 394, 402
Salzburg, 441
Samaná Province, Santo Domingo, 388, 389
Samar, 413
Samarang Island, 190
Samoa, 163, 188
San Ambrosio, 120, 121
San Antonio, Peru, 54
San Antonio, Texas, 394, 396
San Antonio, Vera Cruz, 395
San Benito Islands, 122, 125, 128, 393
San Blas, 133
San Felix, 120
San Fernando, 22
San Francisco, Pachacamac Islands, 32
San Gallán, 15, 21, 23, 44, 63
San Germán, Puerto Rico, 381, 385-387, 480
San Ignacio Lagoon, 129
San Jeronimo, 126
San Jorge Island, 129
San Juan, Peru, 9
San Juan, Puerto Rico, 385, 393
San Juan, Venezuela, 384
San Juan de Nova
 See Juan de Nova
San Lorenz, 102, 108
San Lorenzo Island, 21-23
San Luis Potosi, 395
San Marcial, New Mexico, 398
San Marcos, Texas, 396
San Martin Island, 125, 127
San Pedro Island, 48, 99, 127
San Pedro Martir, 124-127, 131, 344, 362, 367, 465
San Pedro Nolasco Island, 124, 125, 127, 132
San Pietro, 455
San Rafael, 388
San Roque Island, 126, 129
San Saba County, Texas, 395, 397
San Salvador, Bahamas, 392
San Sebastian, 452
San Thomé, 155
Sand Island, Johnston Island, 186
Sand Islet, Midway, 207
Sand Islet, Rose Atoll, 191
Sandakan, 411
sandalwood, Laysan, 205
sandstone, 40, 184, 185, 198, 269, 397
Sandwich Islands, 205
Sangi Sangiang, 285
Sangrang, 285
Sang-Son, 413
sanidine, 198
Sant' Agata d'Esaro, 456, 461
Santa Barbara, Abrolhos Islands, 352
Santa Barbara, Bonaire, 338
Santa Fe, New Mexico, 398
Santa Islands, 21-23, 31, 48, 54
Santa Magdalena Island, 357
Santa Maria, Magdalena Bay, 129
Santa Maria Bay, 129, 134
Santa Maria Island, 47
Santa Rita, 385
Santa Rosa Island, 15, 21-23, 44, 63, 73-76, 81-83
Santadi, 455
Santalum, 205
 cuneatum var. *laysanicum*, 205
Santander, 451
Santita, 31
Santo Domingo, 325, 363, 388
São Paulo, 353
Sao Thomé, 311, 315
Saou, 447
Sarah Anne Island, 190
Sarawak, 410
Sardina sagax, 137, 145
sardine, California, 88
Sardinella stolidifera, 124
sardines, 45, 124, 127, 137
Sardinia, 452, 453
Sardinops caerulea, 85, 86, 124
sarsaparilla, 196
Sassari, 452, 453
Savage Island, 208
Saxifraga cernus, 370
Sayal Island, Mohabbakah Islands, 307, 308
Scaevola, 293
 frutescens, 205
 koenigii, 294
Scala di Gioca, 455
Scarus, 298

- Scenopinus fenestralis*, 405
 Schafgutel, 441
 Schapen Island, 151
 scharizerite, 436, 437, 462
 Scheel Reef, 307, 308
 Schelklingen, 444
 schertalite, 407, 474
 Schio, 456
 schists, 28, 103, 333, 335, 383
 Schouten Islands, 223
 Schwarzgrabenhöhle, 439
Scirpus riparius, 184
 scleroprotein, 388, 406
 scoria, 122, 264
 Scotland, 411, 457
 Scottish Isles, 359
 sea lions, 18, 37, 38, 40, 48, 66, 72, 104, 128, 262, 263
 Sea of Arafura, 276
 Sea of Cortes, 124
 Seal Island, Algoa Bay, 151
 Seal Island, False Bay, 134, 141, 151, 152
 Seal Island, Luderitz Bay, 143, 146, 147
 Seal Island, off Great Paternoster Point, 151, 152
 seals, 5, 37, 38, 40, 45, 52, 72, 92, 140-142, 147, 148, 151, 321
 elephant, 128
 seaweed, 18, 131
 Sebastian Vizcaino Bay, 123
 Sebdoou, 466, 467
 Selankor, 415
 Sella del Diavolo, 456
 Senado, 391
Senecio antipodus, 263, 370
 Senovio Avalos, New Mexico, 398
 Seroe Colorado, Aruba, 341, 342
 Seroe Culebra, Aruba, 341, 342
 serpentine, 275, 346, 478
 Serrana Bank, 317
 Serrana Cays, 320, 321, 344, 345
 Serrana Key, Serrana Cays, 321
 Serranilla Cays, 320, 321
 Serrano Islands, 46
 Serro do Frio, 382
Sesbania, 203
 tomentosa, 203
 sesquioxides, 234, *passim*
Sesuvium, 172, 175, 179, 205, 319
 portulacastrum, 172, 205, 207, 336
 Settle, 457, 458
 Seulo, 456
 Sewanee, Tennessee, 404
 Seychelles, 74, 288, 291, 292, 294, 295, 299, 301, 474
 Shag Island, 356, 357
 shags, 255
 shales, 249, 319, 325, 333
 Shan States, 414, 418
 Shannon County, Missouri, 403
 Shark Bay, 270, 273, 274
 Shark Island, 146
 sharks, 338
 Shaw's Island, 190, 357
 Shay Island, 357
 shearwater, sooty, 112
 shearwaters, 62, 186, 188, 273, 291, 294
 wedge-tailed, 207
 sheep, 441, 457
 mountain, 401
 shell fish-hook culture, Chile, 98, 109, 110, 375
 Shiminato, Tinian, 235
 Shimoni, 420
 Shinan Islands, 282
 Shoal Bay, 274
 shrimp, 153
 Siam, 414
 Sibsey Island, 267
 Sicily, 456
Sida, 179, 272
 fallax, 172, 182, 202
 Sideron Island, 189
 Sierra Bay, 134
 Sigi Caves, 420
 Sigi River, 420
 silcrete, 157
 silica, 73, 85, *passim*
 silicon, 469
 Simud Itam, Borneo, 411
 Simud Putih, Borneo, 411
 Sin Cowe Island, 283
 Sinclair Island, 147, 149
 Siniscola, 453
 sinter, 428, 436, 437
 calcareous, 351, 431, 439
 foliaceous, 431, 432
 Sir Joseph Banks Archipelago, 267, 269
 Siren Island, Cargados Carajos, 293
 skimmer, 60, 105
 skink, 212
 Skipton, 406-408
 Skipton Caves, 406, 474, 475, 482
 skua, 20
 slate, 306
 Sleaford Bay, 268
 Slopen Island, 266
 sloth, giant, 404, 405
 ground, 398, 401
 "Small Island Pajarros," 31
 smelts, 127
 Smith Island, Australia, 268
 Smith Island (Bermeja), 28
 Smoky Bay, 269
 snails, 450
 snake bird, 60
 snakes, 410
 Snares, 260, 262, 263, 370

- snipe, curlew, 187
 snoek, 144
 snow bird, 265
 Socotra, 303–305
 Soda Springs, 402
 sodium, 85, *passim*
 sodium oxide, 73, *passim*
 sodium sulphate, 80, *passim*
Solanum nigrum, 196
 Soledad Bay, 127
 Soledad Rocks, 127
 Somali Current, 304, 365
 Somaliland, 303, 304
 Sombrerillos Islands, 22
 Sombrero Island, 328–331, 344, 345, 362, 363, 376, 377, 465–467, 469, 470
 Somersetshire, 458
Somoplatus substriatus, 420
Somotrichus elevatus, 420
 Songwe River, 419
 Sonsorol Island, 233, 250, 251, 374
 sooty petrel, 305
 shearwaters, 112
 tern, Red Sea, 305
 terns, 166, 172, 182, 185, 197, 201, 207, 236, 270, 273, 290, 305, 312, 368, 369
 Soria, 451
 South Africa, 127, 418
 South Aldabra Island, 292, 297
 South Atlantic Equatorial Current, 315
 South Atlantic Gyral, 136
 South Australia, 409
 South Bat Island, Purdy Islands, 223, 226
 South Bickers Islet, 268
 South Carolina, 393
 South Chinch Island, 33, 34, 37, 38, 40, 41, 63, 68
 See also Chinch Islands
 South Equatorial Current, 5, 7, 9, 121, 160, 290, 311, 345, 365, 482
 South Island, Cosmoledo, 291, 292
 South Island, Macabí, 29, 30
 South Island, New Zealand, 260, 262, 410
 South Island, South West Africa, 147
 South Islet, Caroline Island, 187
 South Long Island, 146
 South Pacific Gyral, 9, 120
 South Pigeon Island, 273
 South Trinidad, 313
 South West Africa, 134–157
 South Whale Island, 129
 Southeast Island, Abrolhos Islands, 352
 Southwest Cay, North Danger Reef, 283, 284
 Spain, 424, 445, 451
 Spanish Pyrenees, 445, 451
 Spencer Bay, 146
 Spencer Gulf, 268
 sperm whales, 162, 163, 260, 270, 278
 spessartite, 333
 sphaerulites, 337, 349–351
 Sphenisciformes, 5, 366
Spheniscus, 61, 62, 94, 141
 demersus, 140, 141
 humboldti, 23, 61, 93
 magellanicus, 355, 356, 358
 spiders, 185, 293, 420
 Spilsby Island, 267
Spondylus, 46
 Sporades, 160, 223
 Spratly Island, 276, 283, 284, 376
 squids, 201, 291
 staffelite, 469
 Stag Island, 151
 stalactites, 204, 214, 220, 239, 309, 310, 326, 329, 382, 393, 409, 410, 412, 422, 428
 stalagmites, 239, 326, 327, 393, 409–411, 423, 428, 457
 Stanley, Falklands, 358
 Starbuck Island, 163, 167, 180, 189, 193, 465
 Staten Island, 355
 Stauperhöhle, 443
 Staver Island, 190
Steatornis, 381
 caripensis, 384
 Stefaniehöhle, 439
 stercorite, 92, 119, 120, 151, 406, 464
Sterna, 62, 89, 165, 175, 214, 332
 anaetheta antarctica, 291
 anaetheta melanoptera, 318, 326, 327
 bengalensis torresii, 256, 270, 272, 368
 bergii, 256, 273
 bergii thalassina, 291
 dougallii arideensis, 291
 fuscata, 5, 120, 133, 186, 236, 256, 291, 293, 294, 296, 305, 313, 314, 327, 333, 347, 367–372
 fuscata crissalis, 197
 fuscata fuliginosa, 290
 fuscata fuscata, 311, 318, 371
 fuscata oahuensis, 165, 175, 185, 201–203, 205–207
 fuscata serrata, 255, 270, 273, 368
 fuscata somalensis, 305
 gracilis, 273
 lunata, 165, 201, 203, 205, 206, 368
 media, 270, 272
 sumatrana mathewsi, 291
 vittata bethunei, 263
 Steward Island, 271
 Stewart Island, 271
Stolidas stolidas, 210
 Stone County, Missouri, 402, 403
 Storm Island, 283
 Strehay Bay, 269
 strengite, 122, 475
Streptococcus allantoicus, 77

- strontium, 300, 468, 473
 struvite, 153, 170, 204, 356, 406–408, 422, 474, 475, 482
 Stumpnose Bay, 139
 Styria, 431, 438
 Subantarctic Islands, 253, 260, 263, 353, 365, 366, 370
 Subantarctic Ocean, 260
 Sugar Loaves, 260, 261, 478
 Sugarloaf Hill, St. Helena, 314
 Sukamawera, 419
Sula, 60, 62, 65, 166, 185, 202, 314, 318, 333, 334, 348, 367
 abbotti, 286, 291, 297
 antiqua, 116
 cyanops, 166, 197, 202
 dactylatra, 53, 120–122, 133, 186, 197, 236, 256, 272, 308, 334, 347, 352, 367, 370
 dactylatra californica, 197
 dactylatra dactylatra, 311, 317, 318, 322, 367
 dactylatra melanops, 291, 304, 305, 367, 368
 dactylatra personata, 165, 166, 201, 202, 205–207
 fusca, 285
 gossi, 131
 leucogaster, 186, 187, 197, 236, 265, 285, 286, 291, 305, 318, 320, 347, 353, 366, 368, 370
 leucogaster albiceps, 125, 196
 leucogaster brewsteri, 125, 126, 129, 131–133, 196, 367, 368
 leucogaster etesiaca, 196
 leucogaster leucogaster, 158, 311, 317, 319, 322, 325, 327, 333–335, 346, 367
 leucogaster nesiotes, 125, 133, 196, 197, 367
 leucogaster plotus, 165, 166, 169, 182, 200–202, 205, 255, 256, 259, 272, 299, 368
 nebouxii, 21, 26, 28–30, 51, 54, 63, 65, 87, 125, 126, 131, 366
 piscator, 165, 166, 202, 210, 212, 296, 320
 piscatrix, 285
 sula, 125, 166, 187, 197, 202, 236, 265, 285, 301, 314, 319, 320, 333, 334, 370, 371
 sula rubripes, 166, 168, 182, 185, 187, 191, 201–203, 205–207, 210, 212, 236, 256, 286, 296
 sula sula, 291, 292, 294, 317, 318, 326, 327
 variegata, 19–21, 29, 30, 32, 47, 51, 54, 59–61, 63, 66, 67, 73, 74, 86, 116, 367, 481
 Sulidae, 141, 200, 256, 366, 367
 sulphates, 73, *passim*
 sulphur, 204, *passim*
 Sulu Sea, 276, 278
 Sumatra, 413
 Šume, 427
 sunbird, 214
 Supe, 52
 Surprise Island, 258, 259
 Suvarov Island, 188, 190
 Svrljig, 426
 Swains Island, 190
 Swakopmund, 136
 Swans Islands, 318, 319, 344, 345, 362
 Sweden, 423
 swifts, 410, 411
 Switzerland, 424
 Sydney Island, 164, 177, 178, 180, 191, 470
 syenite, 113
 Sylviidae, 167
 Table Bay, 141, 151
Tachypetes ariel, 285
Tadarida, 389, 403
 cynocephala, 394
 macrotis, 389
 mexicana, 393–395, 401
 mexicana mexicana, 397
 murina, 385, 389
 Tafelberg, Santa Barbara, Curaçao, 338–340
 Tahiti, 163, 182, 188, 210
 Taiping, 415
 Taiwan, 249
 Talara, 53
 Taltal, 48
 Tamaokidaira basin, Kita Daito Jima, 238–241
 Tambang group, 413
 Tanga Caves, 420
 Tanganyika Territory, 304, 419, 420
 “tanghain,” 296
Tanupalama, 402
 Taogni, 228
 Tapanoeli, 413
 Tapaste, 390
Taphozous mauritianus, 420
 tapir, 450
 Tarama Jima, 247, 249, 251, 252, 378
 Taranaki, 260, 261
 taranakite, 261, 266, 275, 355, 356, 409, 410, 421–423, 436, 449, 457, 478–480, 482
 Tarapacá, 44, 45, 47, 95
 Taritari, 189
 Tarn, 444–446
 Tarn et Garonne, 444, 446
 taro, 168
 Tarragona, 452
 Tartacay, 22
 Tasmania, 253, 264–266
 Tau Island, 191
 Taubenloch, 439
 Tavoy, 418
 Tayabas, 413
 Taylor Island, 268
 taylorite, 61, 91, 92, 94, 463, 481
 teal, Laysan, 201
 Teinhoven, 190
Telespiza cantans, 201
 ultima, 201
 Tenasserim, 418

- Tennessee, 394, 404, 474
 Tennessee River, 402
Terebralia gourmyi, 238
 termites, 4
 tern, bridled, 326
 Inca, 21
 Red Sea sooty, 305
 Ternas, Makatea, 209
 terns, 5, 51, 52, 62, 120, 125, 165, 166, 175, 187,
 200, 201, 205, 248, 255, 256, 265, 291, 293,
 307, 313, 318, 322, 327, 333, 367, 368, 370, 371
 noddy, 187
 sooty, 166, 172, 182, 185, 197, 201, 207, 236,
 270, 273, 290, 305, 312, 368, 369
 terra rossa, 231, 232, 239, 252, 377, 482
 teschemacherite, 40, 77, 93, 357, 464
 Testigo Grande, 333
 Testigos Island, 317, 345, table 54
Testudo abrupta, 292
 audinii, 292
 elephantina, 292
 gigantea, 292
 gouffeii, 292
 grandidieri, 292
 sumieri, 292
 Teufelslochhöhle, 424, 429
 Teufelslucke, 439
 Texas, 393-397, 399, 405
 textiles, beneath guano, 30
 Thai-huyen, 413
Thalasseum bengalensis torresii, 255
 bergii gwendolena, 255
 Thanh-Hoa, 413
 Thaurerschluft, 441
 Thistle Island, 268
 Thi-tu Island, 283, 284
 Thi-tu Reef, 283
 Thompson Island, 269
Thyrates, 145, 146
 atun, 144, 145
 Tiau-su, 248
 Tiburon Island, 124, 129, 130
 ticks, 17, 19
 Tienhoven, 189
 Tierra del Fuego, 21
 Tierras Nuevas, Camp Alegre, 385
 Tiger Bay, 134
 Tigre, Pabellón de Pica, 102
Tillaea moschata, 262, 370
 Timok, 426
 Timor, 276
 tineid moths, 420
 Tinian, 235, 251, 252, 376-378
 Tipaza, 422
 Tischerferhöhle, 441
 Tissi, 455
 titanium, 157, 158, 263, 476
 titanium phosphate, 264
 Tizard Bank, 283
 Tlemcen, 422, 423
 tobacco, 207, 305
 Tobi Island, 232
 Tocopilla, 112
 Togobei, 229, 232, 233, 236, 250, 251, 374, 375
 Tokelau group, 190
 Tonga group, 208, 222
 Tongan structures, 184
 Tongareva, 189, 190
 Topolobampo Bay, 124, 125, 132
 Tori Shima, 248, 250, 377, 378
 Toro Wado Remba, 285
 Torquay, 458
 Torres Strait, 255
 tortoises, 292, 295-298, 330
 Tortoli, 456
 Tortosa, 452
 Tortuga, 31
 Tortugas Island, 15, 22
 tosca, 115, 116
 To-shu Tao, 279
Totanus, 187
 Tour Combes, 423, 467, 479
Tournefortia, 163, 165, 166, 177, 178, 184, 187,
 235, 293
 argentea, 182, 184, 294
 trachyte, 195-198, 260, 315, table 54, 478
 Tragó de Noguera, 452
 Transvaal, 418, 419, 477
 Transylvania, 427, 428
 Transylvanian Alps, 428
 Trauhira, 349, 351, 478
 travertine, 269, 457, 458
 Travis County, Texas, 395
 Tree Island, Paracel Reefs, 279, 282
 trek duiker, 140, 141, 144
 Tremp, 452
 Tres Marias Islets, 22
Triaenops afer, 420
 Triangle Key, Serrana Cays, 321
Tribatus cavernicola, 420
Tribulus cistoides, 172, 186
 Trinidad, 327
 Tristan da Cunha group, 353
 Triton Island, Paracel Reefs, 279
 Trommelin Island, 229
 trophophoric field, 3-5, 373
 tropic bird, red-billed, 314
 red-tailed, 166
 tropic birds, 132, 181, 305, 347
Tropidurus peruvianus, 19
 Trou de Capuchin, 446
 Truk Archipelago, 229
 Tsarabanja, 421
 Tschernerwandhöhle, 439
 Tsingilofilo Reef, 300

- Tuamotu group, 160, 168, 182, 184, 186, 208, 210, 212
 tubipores, 280
 tuff, 202, 287, 395, 399, 402
 Tukang Besi group, 284
 Tuléar, 421
 tuna, 327
 Tung-sha-tao, 278
 Tunis, 424
 Tunnel du Cormoran, Réunion, 421, 463, 474, 480
 Turdos, 429
 Turkey, 381
 turkey buzzards, 33, 51
 vultures, 18, 21
 Turk's Cap Bay, St. Helena, 314
 turnstones, 290
 turtle, 210
 Tuyen-Quang, 413
 Tyrol, 441
Tyto ostologus, 389

 Ubrique, 452
 Udot Island, 229
 Ukinga, 420
 Ulassai, 456
 ungulates, 381
 Union group, 190
 United States, guano deposits, 393 *et seq.*
 Untersberg, 441
 Upolu, British Samoa, 188
 Upper Humboldt Lake, Nevada, 133
 urea, 4, 5, 77, 381, 402, 422, 461, 462
 uric acid, 71, 77, *passim*
 urochrome, 75
Ursus spelaeus, 428, 433, 437, 438, 443, 449, 474, 480
 Uruguay, 382
 Urukthapel Island, 232, 252, 377, 378
 Urukutaburu Island, 232
 Urzulei, 455, 456
 Utah, 402
 Utuado, 385
 Uvalde, 396
 Uvalde County, Texas, 395

 Val Verde County, Texas, 397
 Valencia, 451
 Valparaiso, 53
 vampire bats, 395
 Van Link, 413
 vanadium, 468, 474
 Vancouver Island, 124
 Vaour, 445
 variscite, 122, 157, 159, 204, 329, 333, 436, 475, 476, 480
 Vaşcău, 427, 428
 vashegyite, 261, 478
 Vavau, 222

 Vega Baja, 385, 387
 Vejer, 452
 Vejer de la Frontera, 452
 Vela Rock, 124, 128, 129
 Venezuela, 322, 331-333, 337, 365, 382-384
 Venezuelan Leeward Islands, 315, 317, 318, 332, 333, 345, 367
 Venus Bay and islands, 269
 Vera Cruz, 395
Vermetus, 338
Vespertilio murinus, 443
 olivinus, 425, 450
 subulatus, 403
 vespertilionid bats, 423, 424
 Vicenza, 456
 Victoria, Australia, 264, 406
 Victoria Cave, Yorkshire, 458
 Victoria Island, 190
 vicuña, 112
 Vieja, 15, 21-23, 44
 Villa de Cura, 384
 Villa Garcia, 395
 Villach, 438
 Villanua, 451
 vines, 223
Vini kuhlii, 167, 184
 stepheni, 212
Vireosylva gracilirostris, 347
 Virgin Islands, 327, 344
 Vivario Cays, 319
 Vivero, 28
 vivianite, 266, 267
 Vivorilla Cays, 317, 319, 344, 376
 Vizcaya, 451
 Vizeu, 348
 Völkermarkt, 438
 Voiteur, 447
 Vonderling Island, 140, 141, 151, 152
 Voralberg, 441
 Vostok Island, 188, 190, 191, 223
Vultur gryphus, 18
 vultures, 52
 turkey, 18, 21
 Vusta Island, 307, 308
 Vypustek Cave, 441, 442

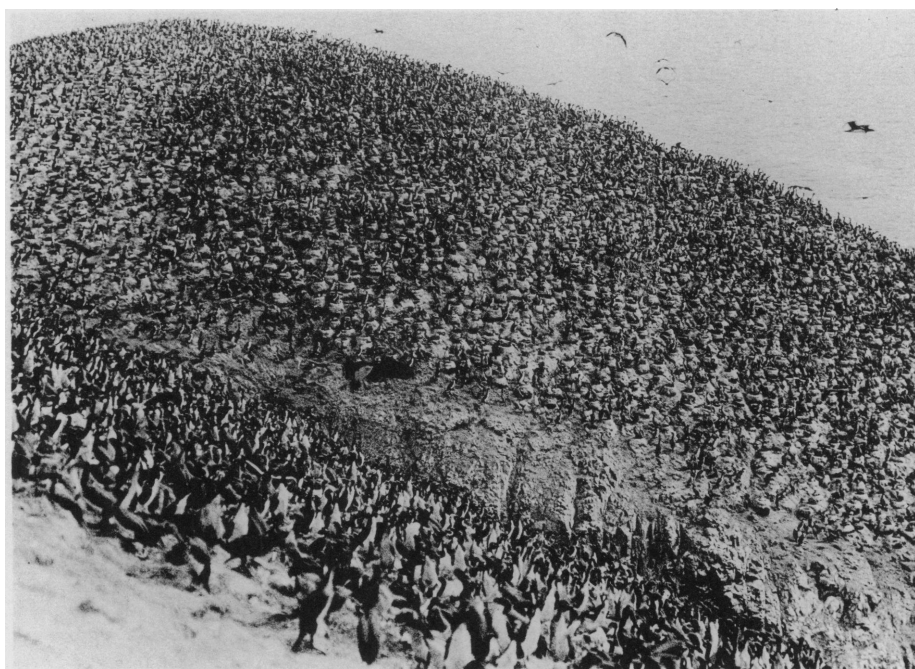
 wader, 62
 Waiawa, 200
 Waidhofen, 439
 Waldegg, 439
 Waldegrave Islands, 269
 Wales, 458
 Walker Island, 190
 Wallabi group, 273
 Walpole Island, 253, 259, 364, 376-378, 473
 Walvis Bay, 134, 136, 139-141
 warbler, Nauru nightingale reed, 214
 warblers, 167, 201, 210, 213, 214

- Ward's Rock, 268
Warren County, Tennessee, 404
Warrnambool, Australia, 406
Washington Island, 163, 165, 167, 183-185, 192, 194, 195, 364, 370, 374, 375
Washoe County, Nevada, 401
Watling Island, 392
wavellite, 243, 261, 349
Wayne County, Idaho, 402
Wedge Island, 268
wedge-tailed shearwaters, 207
Weelhamby Lake, 275, 477, 478
Weissenbachhöhle St. Lorenzen, 438
Weitzen, 429
Weiz, 438
Wellington Caves, New South Wales, 409
Wellington Valley, 409
West Australia, 410
West Faiu, 227
West Indies, 315, 317, 318, 328, 331, 332, 376, 377, 381, 391, 392, 465, 466, 475, 476
West Island, Ashmore Shoals, 271
West North Island, Cosmoledo, 291
West North-East Island, Cosmoledo, 297
West Virginia, 394, 405
West Wallaby, 273, 274
West York Island, 283
Whakari, 261
whale, right, 260
Whalers Anchorage, Fanning Island, 183
whales, sperm, 162, 163, 260, 270, 278
whewellite, 92, 462
White Cavern, Borneo, 411
White Friars, 133
White Island, Bay of Plenty, 261
White Islet, near Dunedin, 262, 478
White Islet, west of Australia, 272
White Rock, Las Tres Marias Islands, 133, 367
White Rocks, Tasmania, 266
white-headed noddy, 291
whitlockite, 331, 341, 343, 344, 464-467
wideawake, black, 175
Wideawake Fairs, 311-313, 368
wideawakes, 165, 181, 186, 187, 290, 291, 294, 332
"widiawabus," 332
wild rock doves, 411
Wildalpen, 438
Wildcat Canyon, Utah, 402
William Pitt Bay, 299
Williams Island, 268
Williamson County, Texas, 395
Willis Island, 255
Winceby Island, 267
Winhelman, Arizona, 401
wire bird, 313, 314
Wirshofhöhle, 441
Wirwutu, Ninigo Islands, 374
Wizard Island, Cosmoledo, 290, 292, 297, 302
Wollersdorf, 439
"wolves," 418, 419
Wonderfontein, 418
Wooded Island, 273
Woody Island, Indian Ocean, 299
Woody Island, Paracel Reefs, 278, 279, 376
Wookey Hole, 458
Wool-shed Imperial Cave, New South Wales, 409
Wreck Reef, 256, 257
Wusta Island, 307
Wuvulu Island, 226

xanthine, 75, 77
xanthopterine, 75

Yavapai County, Arizona, 401
Yavaros, 124
Ybbs River, 439
yellow-footed booby, 335
Yonne, 444
Yorkshire, 457, 458
Yoron Shima, 248, 377, 378
Yucca, 401
Yugoslavia, 425, 426

Zacoalpan Amilpas, 395
Zanzibar, 303-305, 420
Zarate Islets, 22, 44
Zaratillo, 44
Zebra, Missouri, 402
Zenaida auriculata noronha, 347
zeugite, 331, 466
Ziegenstall, 443
zinc, 340, 448, 449, 474, 476, 480
Zlot, 426
Zoetendalesvley 889, 477
Zostera nana, 125
Zoutpansberg, 419



1. Guanay colony, Pescadores Island, December, 1919. 2. Guanays on nest, Pescadores Island, December, 1919. Both after Murphy

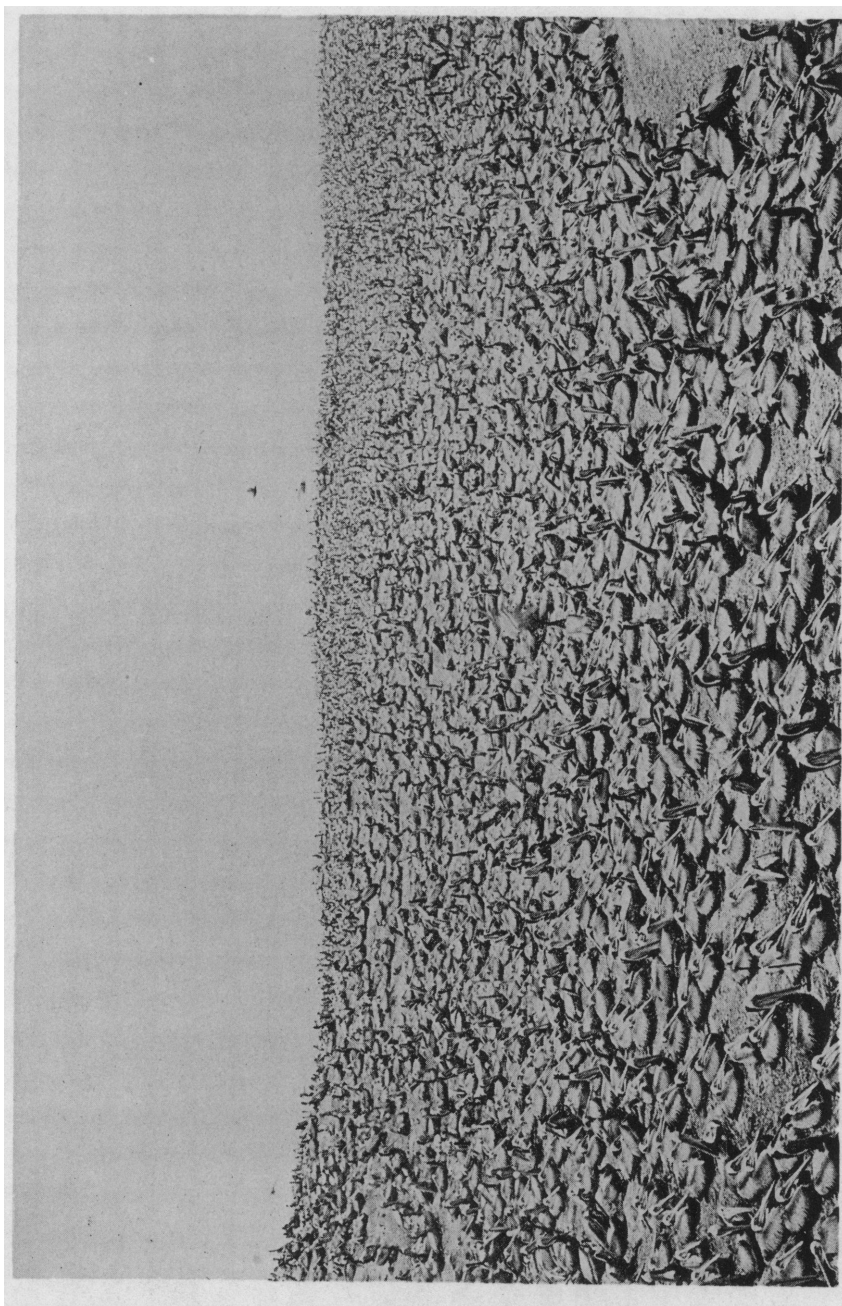


1

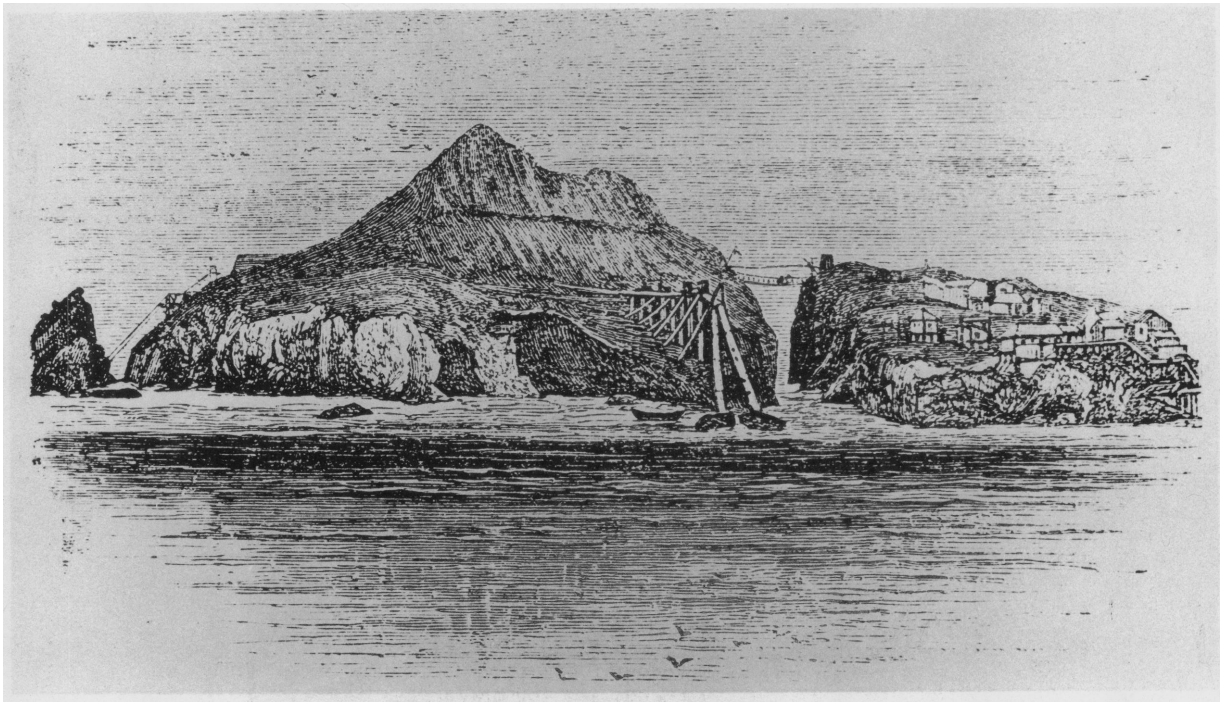


2

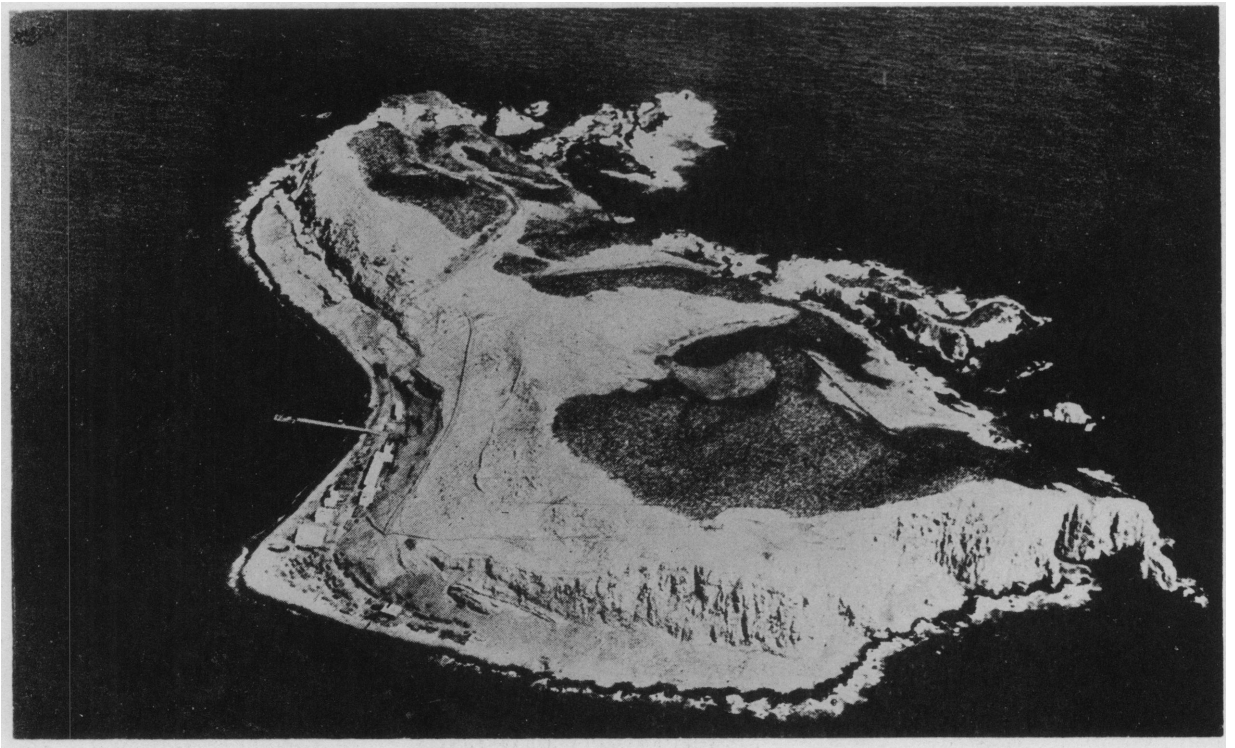
1. Nesting place of piqueros, *Sula variegata* (Tschudi), Chincha Islands, June 12, 1908. After Coker. 2. Piqueros nesting on South Guañape Island, New Year's Day, 1920. After Murphy



Portion of nesting ground of pelicans, Lobos de Afuera, West Island, December 3, 1907. After Coker

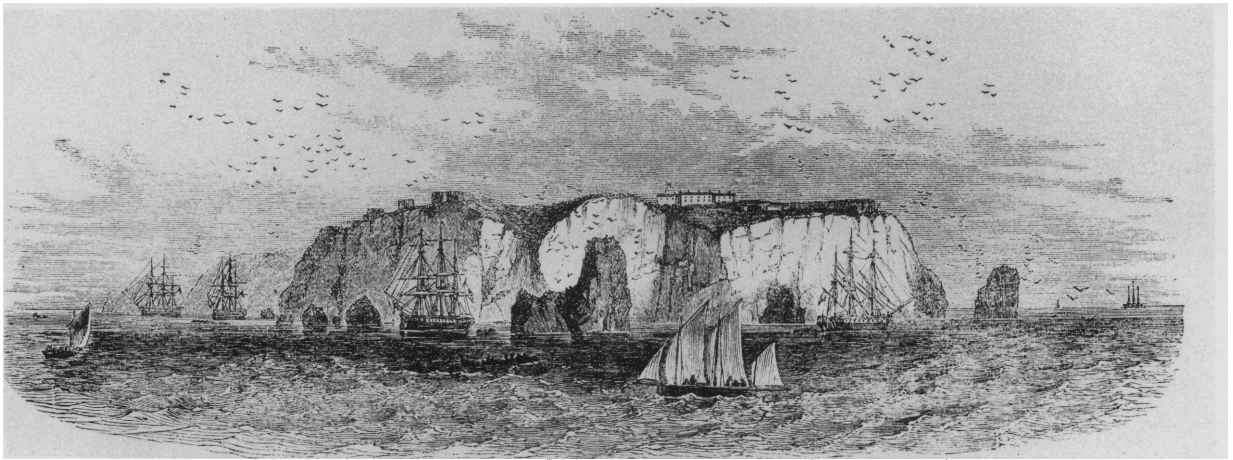


1

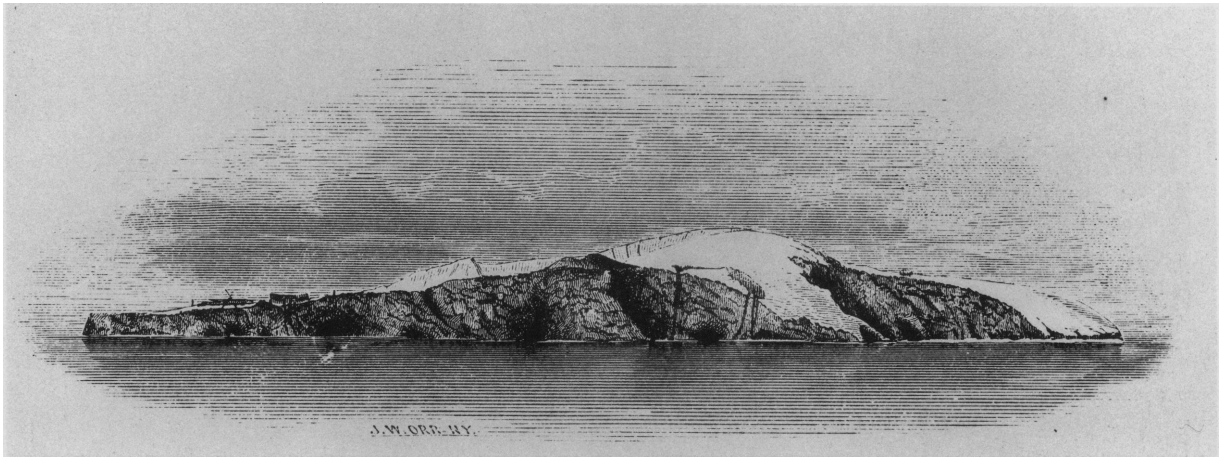


2

1. Macabí Island. After Hutchinson. 2. North Guañape Island. After Murphy



1

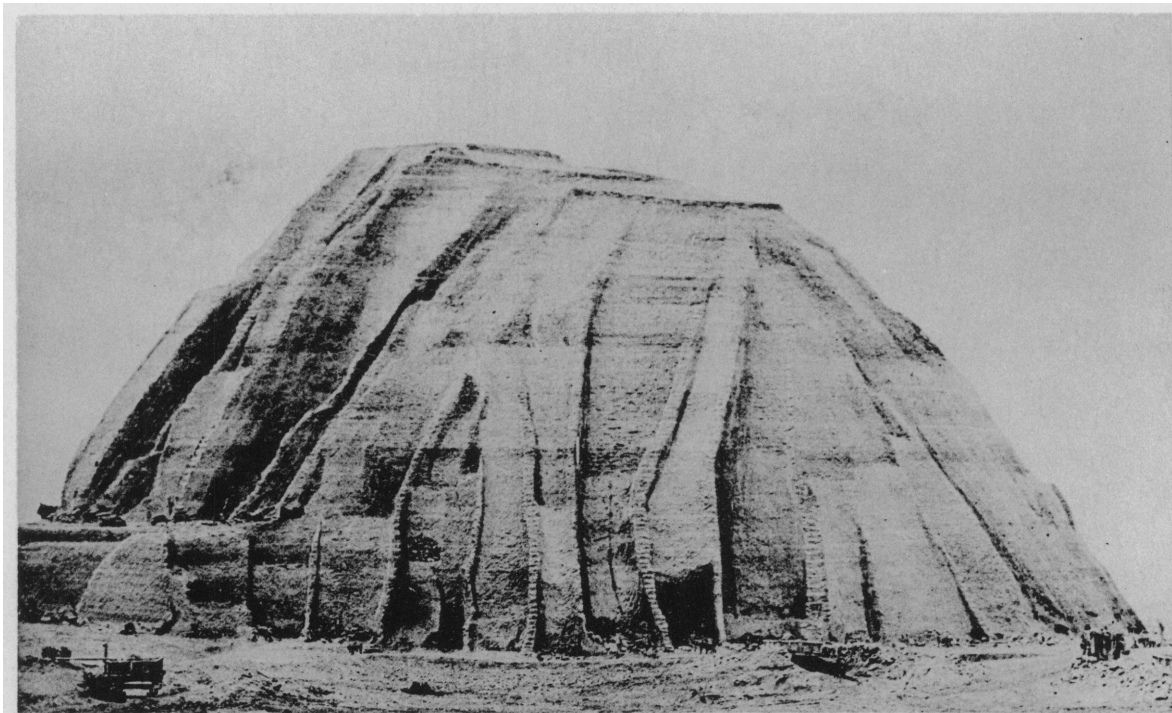


2

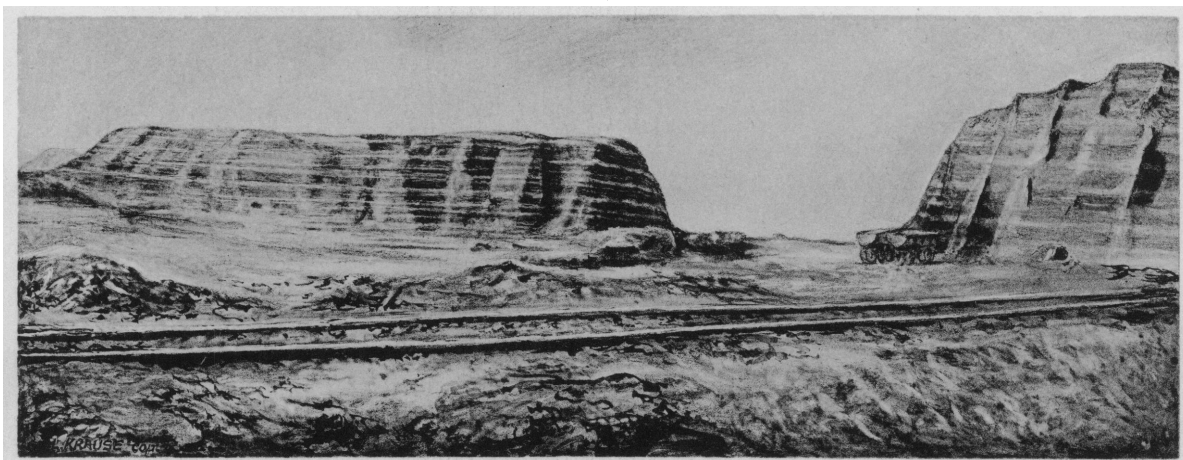


3

1. North Chincha Island. After the Illustrated Times, London. 2. Central Chincha Island. After Peck. 3. South Chincha Island. After a photograph by Merriman in Murphy

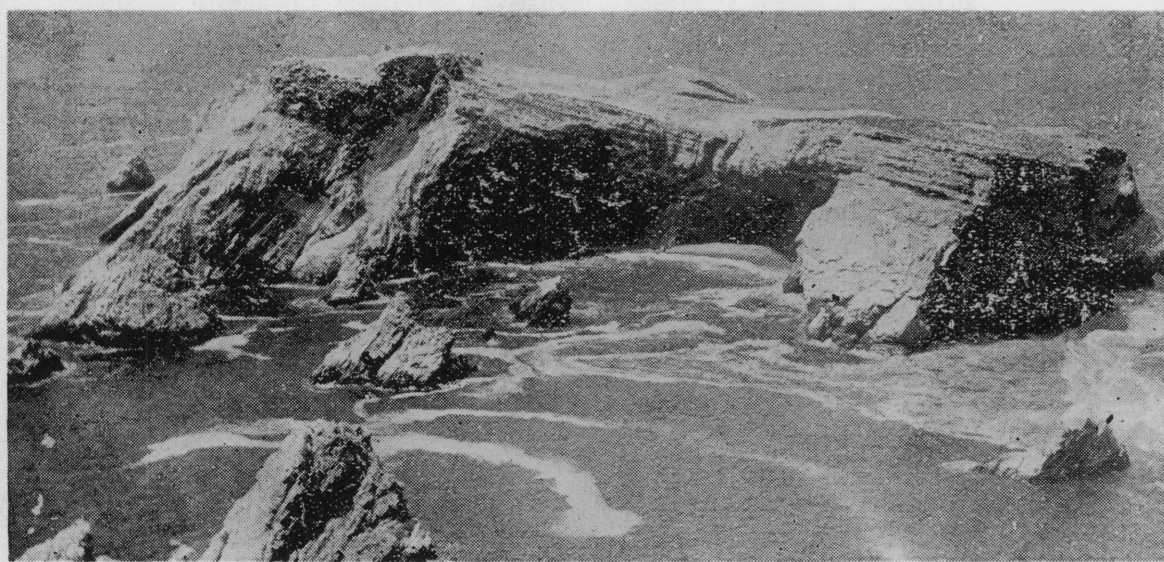


1

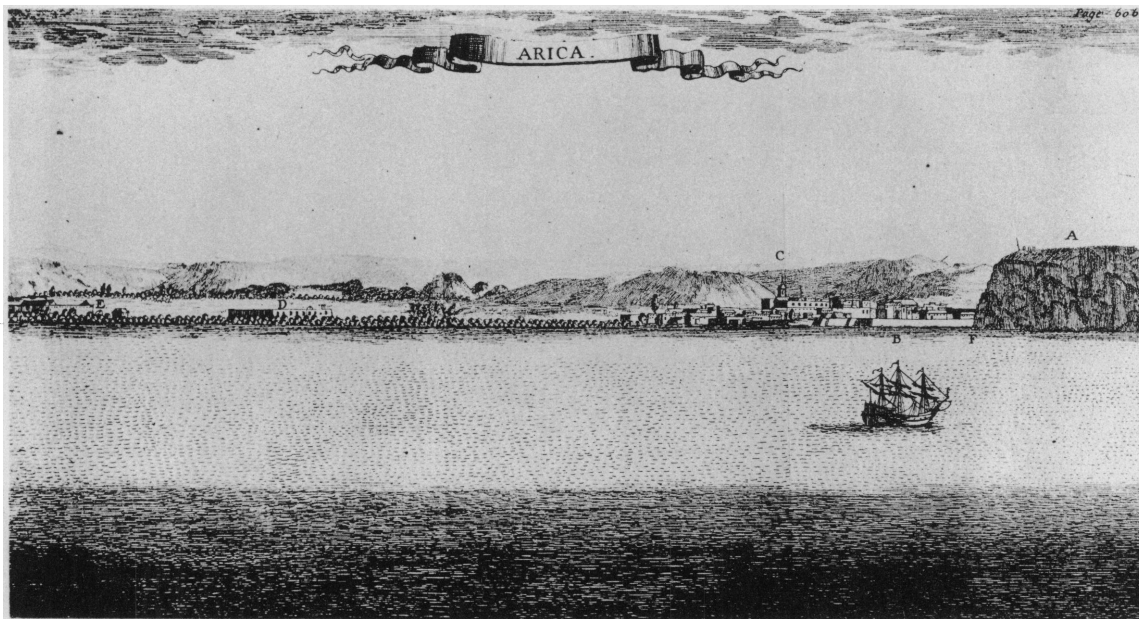


2

Residual guano cap on North Chincha Island. 1. Enlarged from a photograph by Merriman. 2. Redrawn from photographs in possession of Compañía Administradora del Guano, Lima



1

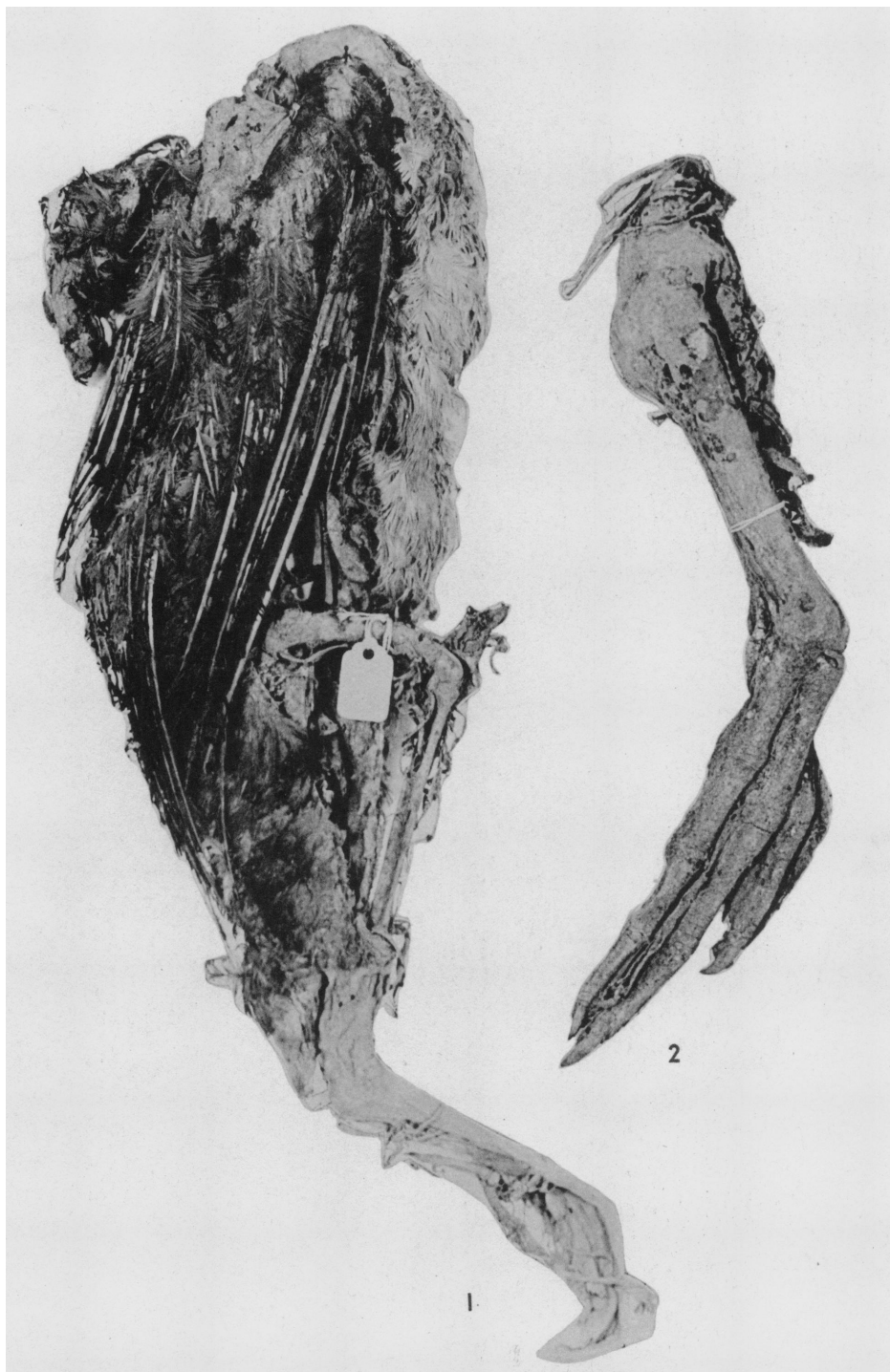


2

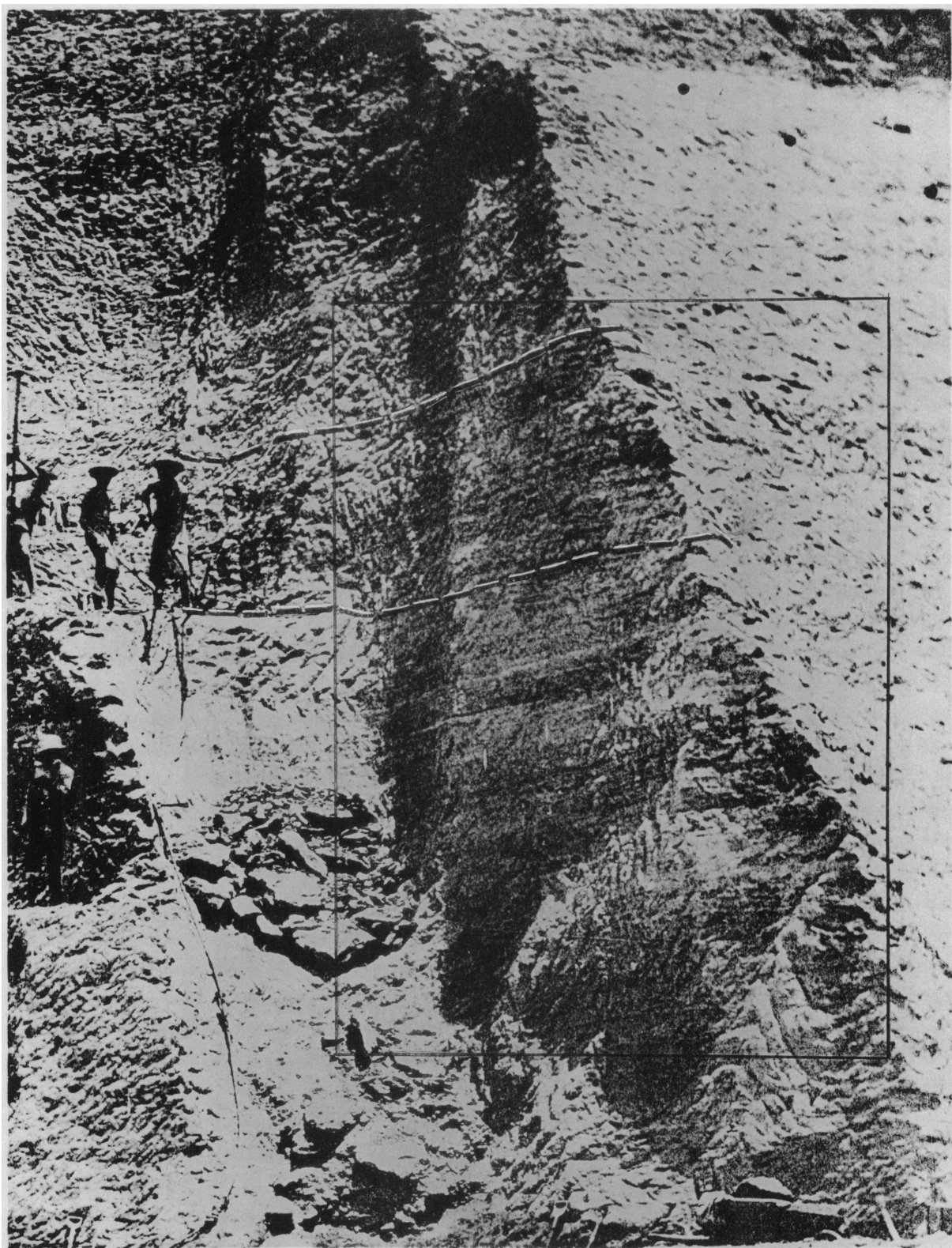
1. North Ballestas Island. After photograph in the Boletín de la Compañía Administradora del Guano, Lima. 2. Arica and Alacran Island (A). After Feuillée



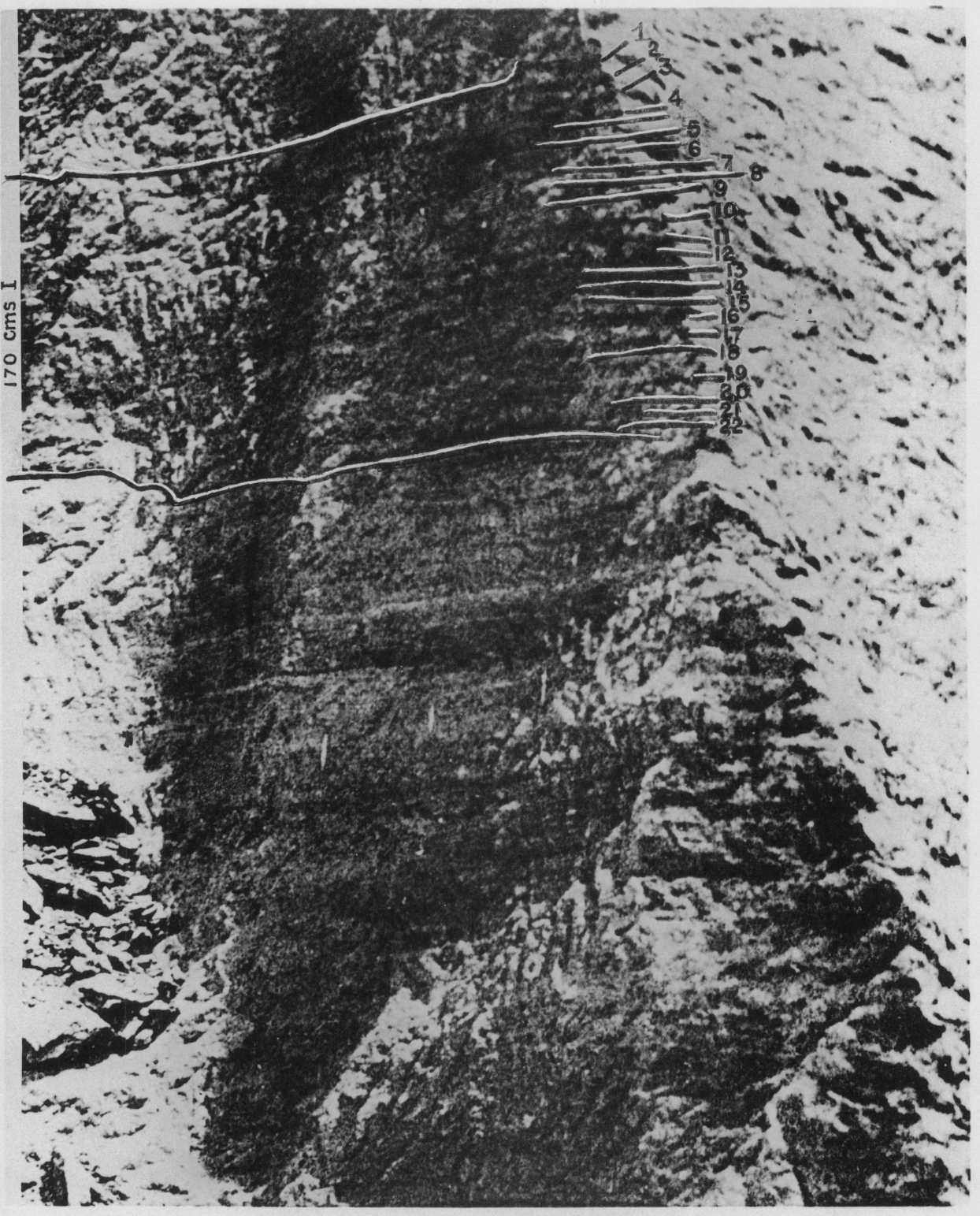
1. Ceramic of Bird Island in the Museum at Hacienda Chicln. 2. *Spheniscus* egg, Columbia University. 3. *Pelecanoides* egg, the American Museum of Natural History



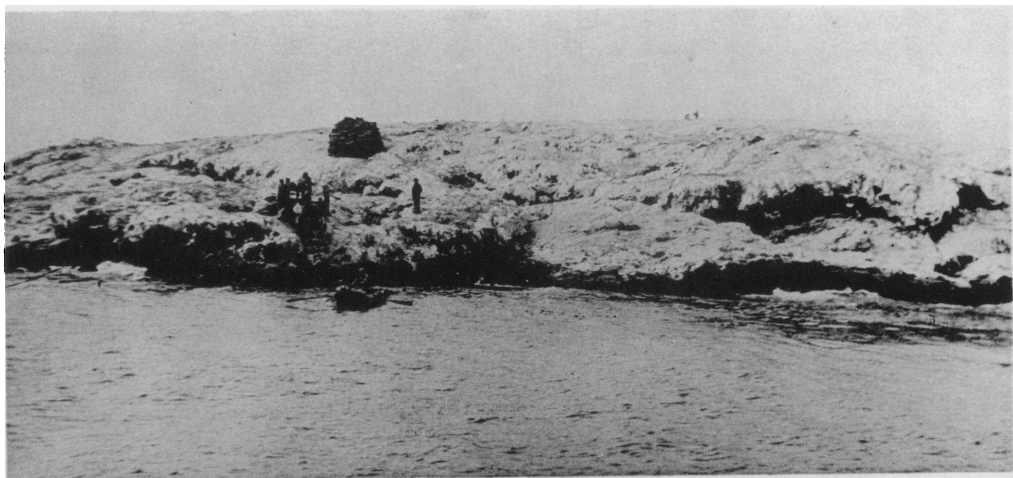
Mummified birds from Guañape Islands, Peabody Museum, Yale University. 1. *Phalacrocorax bougainvillei*. 2. Leg of *Pelecanus o. thagus*



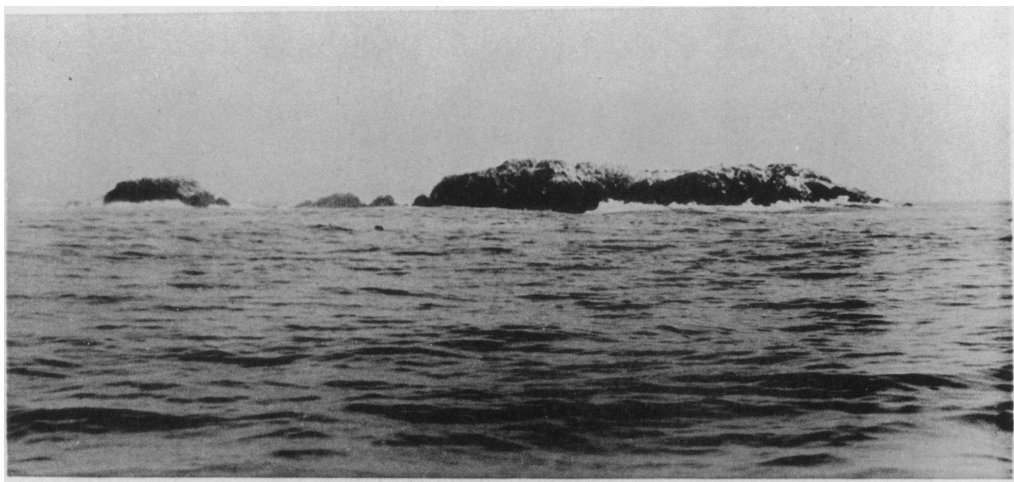
Section of guano face of Central Chincha Island, from a photograph by Merriman.
Compare plate 13 in Murphy, 1936



Enlargement of the portion of the guano face of Central Chincha Island indicated in plate 10, to show stratification



1



2

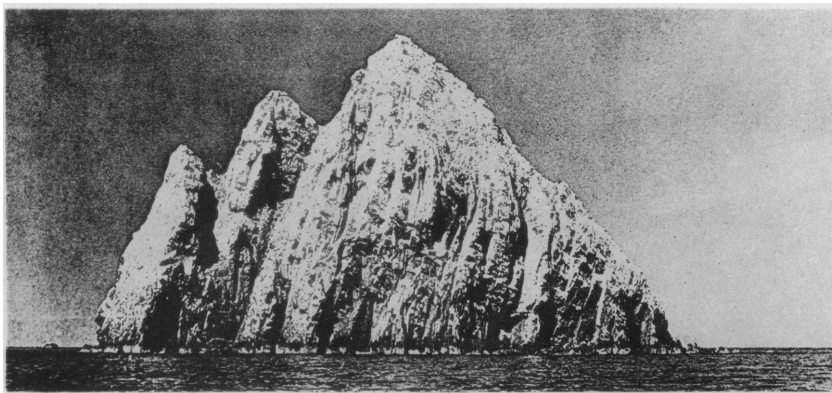


3

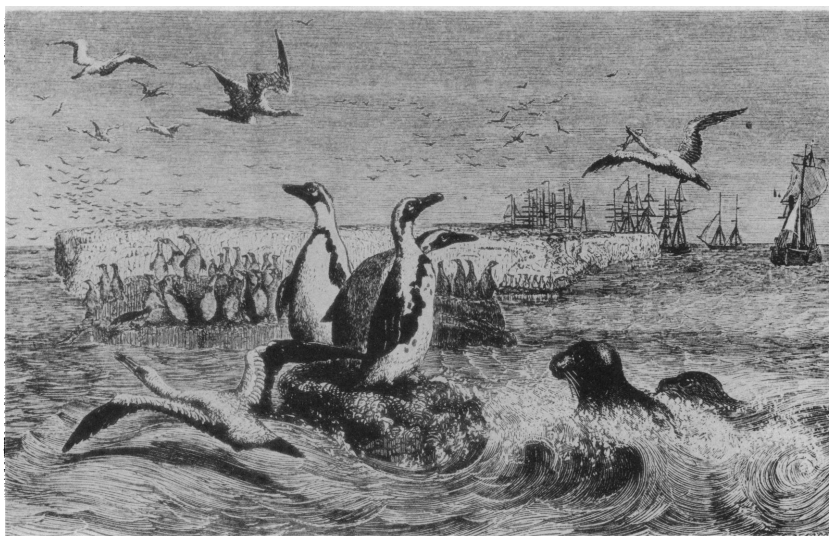
Guano islands of Lower California. 1. Elide. 2. Colorado. 3. Maria Rock. After George W. Beermaker, Inc.



1

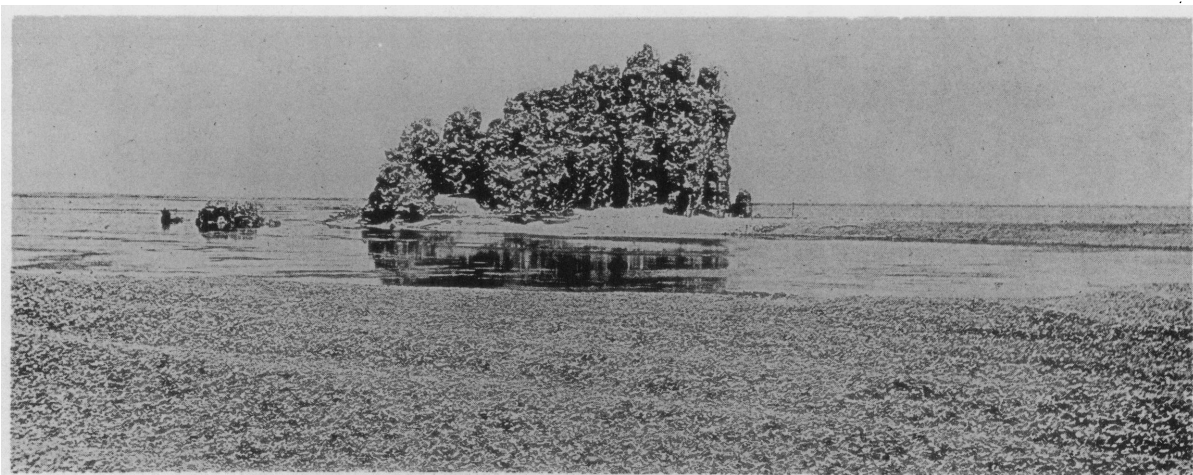


2



3

1. Collection of guano, Magdalena Bay. After George W. Beermaker, Inc.
2. Farallon de San Ignacio. After Fraser. 3. Ichabo Island. After "Ex-Member of Committee"

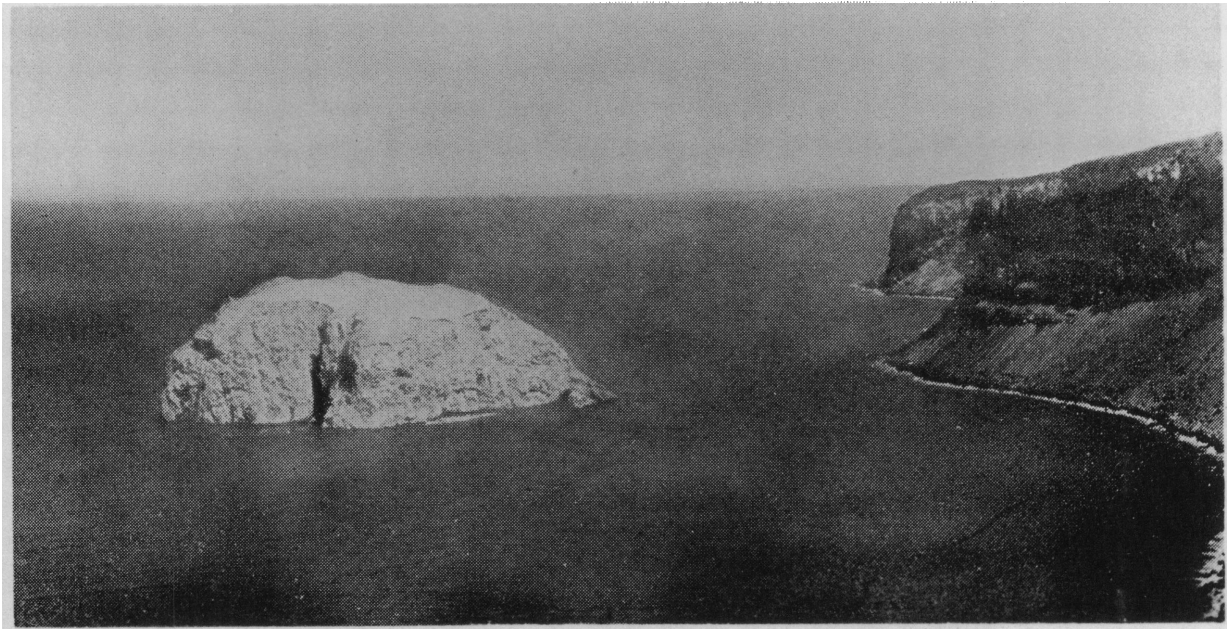


1

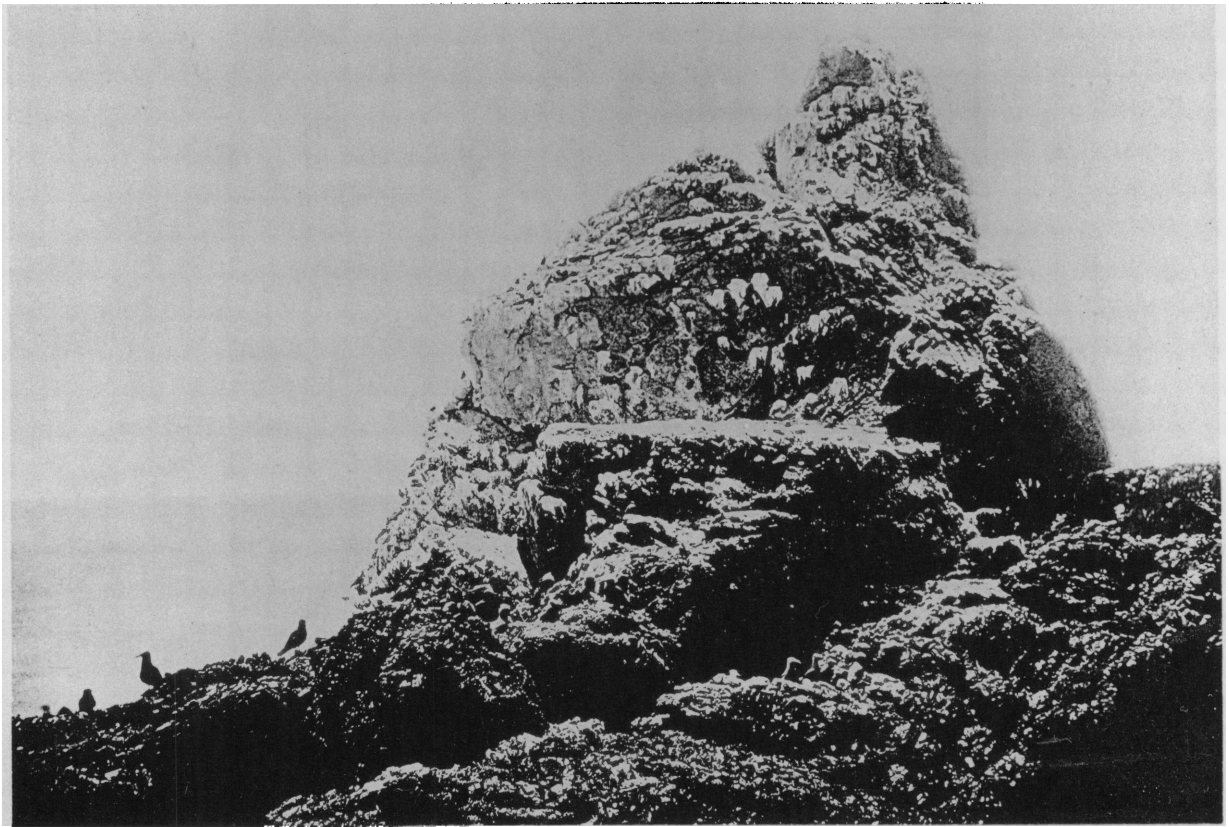


2

1. Rock in the atoll rim of Clipperton Island. After Wharton. 2. Karrenfeld in the exploited region of Makatea. After Elschner

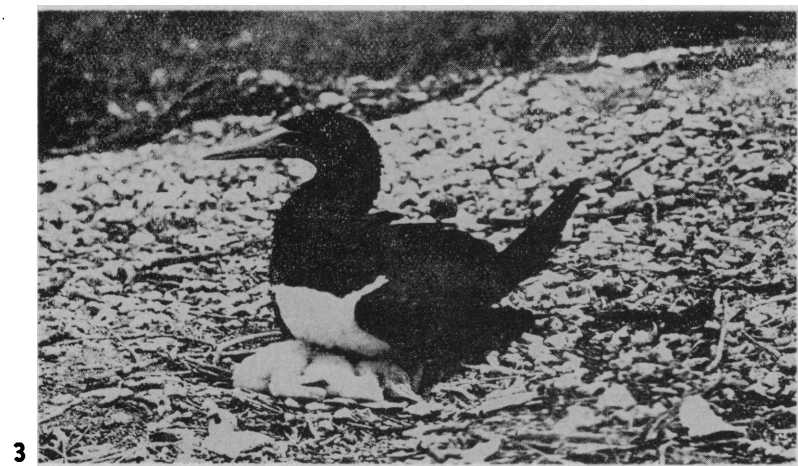
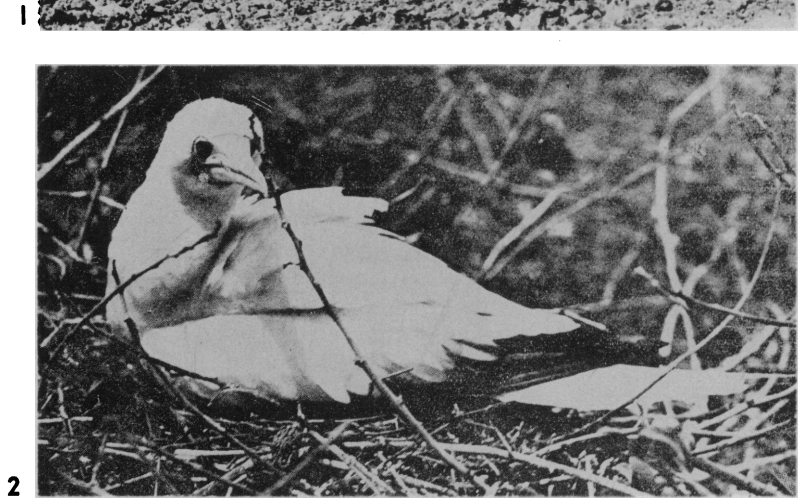


1



2

1. Boatswain Bird Island. After Chapin. 2. St. Paul's Rocks. After report of the "Challenger" expedition



1. Pacific masked booby, *Sula dactylatra granti*, nesting on San Felix Island. After Murphy. 2. Red-legged gannet, *Sula sula rubripes*, on nest. Raine Island. After North. 3. Brown gannet and young, *Sula leucogaster plotus*. Raine Island. After North

